EVALUATION OF SHELTER VENTILATION BY MODEL TESTS

GARD FINAL REPORT A1-51

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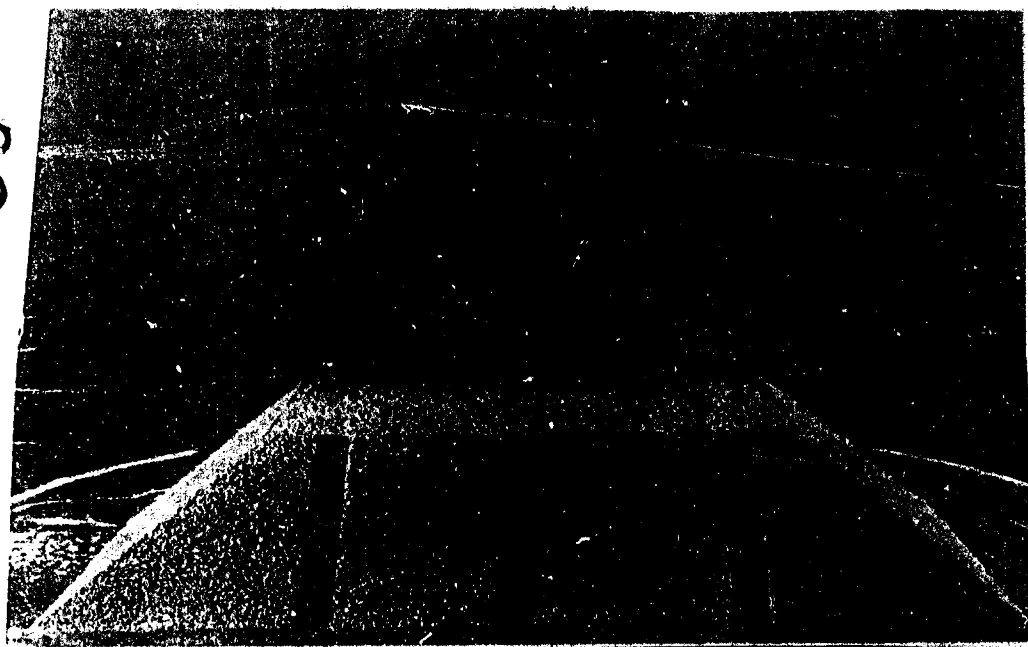

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Scale model tests using a low speed wind tunnel were performed to determine the wind-induced ventilation throughput in an earth-bermed, single-room, above-ground shelter over a wide range of approach wind velocities. Air flow through the wall openings and the interior of the model was traced with neutrally buoyant tracer bubbles and recorded using a movie camera. Volume flow rate through a door or window opening was determined by taking the product of the average bubble velocity, the area of the opening and an experimentally determined area coefficient. Model ventilation throughput values were obtained

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A simple design of a Flow Enhancement Device (FED) which could significantly improve wind-induced ventilation in a below-ground shelter was concepted. A scale model of a 100-person, key worker type below-ground shelter was fabricated and preliminary runs were made with it.

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DETACHABLE SUMMARY

EVALUATION OF SHELTER VENTILATION BY MODEL TESTS

GARD FINAL REPORT A1-51

March, 1983

FEMA Work Unit 1217I

by

C. K. Krishnakumar
J. B. Koh
S. F. Fields
R. H. Henninger

for

Donald A. Bettge
FEDERAL EMERGENCY MANAGEMENT AGENCY
Washington, D.C. 20472

under Contract No. EMW-C-0633

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INTRODUCTION

This study was performed with the following objectives:

- Establish an empirical correlation between the wind-induced ventilation throughput (cfm) and the approach wind velocity for a basic one-room, above-ground, bermed shelter with an occupant density of 1 person per 10 square feet.
- Analyze and compare the air flow distribution inside the shelter for different wind conditions.
- Establish a test scheme to study wind-induced ventilation in below-ground key worker shelters.

The adequacy of shelter ventilation depends both on the ventilation throughput (cfm) and the air distribution. The ventilation throughput and air distribution in a given shelter depend on the approach wind speed, the relative wind angle and the geography of the location. In the present study, a scale model test technique using flow visualization in a low speed wind tunnel was used to evaluate the ventilation throughput (cfm) as a function of approach wind velocity for a shelter situated in a suburban area with small bushes. Air flow distribution in the model shelter was analyzed using a temperature-decay method at two values of wind speeds and relative wind angles. For ventilation studies of below-ground shelters, a scale model of a 100-person key worker shelter was fabricated and suspended below the transparent Plexiglas turntable in the wind tunnel's test section. Preliminary tests made with a simple design of a 'flow enhancement device (FED)' indicated that substantial improvements in natural ventilation of these shelters could be achieved with the use of FEDs.

MODEL TESTS

To determine model ventilation throughputs, the flow visualization technique developed by GARD in its previous study was employed. This technique involves the tracing and photographic recording of path lines of neutrally buoyant tracer bubbles passing through the model openings and determining the average bubble velocities from these recordings. The air volume flow rate through an opening is obtained as the product of the average bubble velocity through that opening and the bubble through-flow area. Model ventilation throughput values are obtained by adding the air volume flow rates through all the inlet openings. Ventilation rates for the full-scale shelter are calculated from those of the model using appropriate scaling laws.

RESULTS

Projected values of ventilation throughput (cfm) as a function of wind speed and wind angle for the full-scale shelter are shown in Figure 1. The following observations were made:

- Ventilation throughput (Q) is a strong function of wind speed (V). In the range of wind speeds tested, the slope of the ventilation throughput versus wind speed curve $(\frac{dQ}{dV})$ increases with wind speed.
- Ventilation throughput has only a weak dependence on wind angle. For shelter orientations at which the wall with the larger opening area is on the windward side, ventilation throughput is slightly higher than for cases in which it is on the leeward side.

Air distribution (fresh air mixing) inside the shelter depends on both the wind speed and the relative wind angle. Figures 2 and 3 illustrate the effects of wind speed on air distribution inside the shelter at a full-scale elevation of 5 feet from the floor. It appears that a shelter similar to the one studied would meet the ventilation requirements for an effective temperature of 83°F and 90% adequacy over a significant portion of the United States if moderate wind speeds (not less than ~ 8 mph) prevail.

Preliminary tests made with the scale model of a single-chamber, below-ground shelter (Figure 4) indicate that the air volume flow rate can be increased considerably by properly designed FEDs. Additional studies to otpimize the design and location of FEDs are strongly recommended.

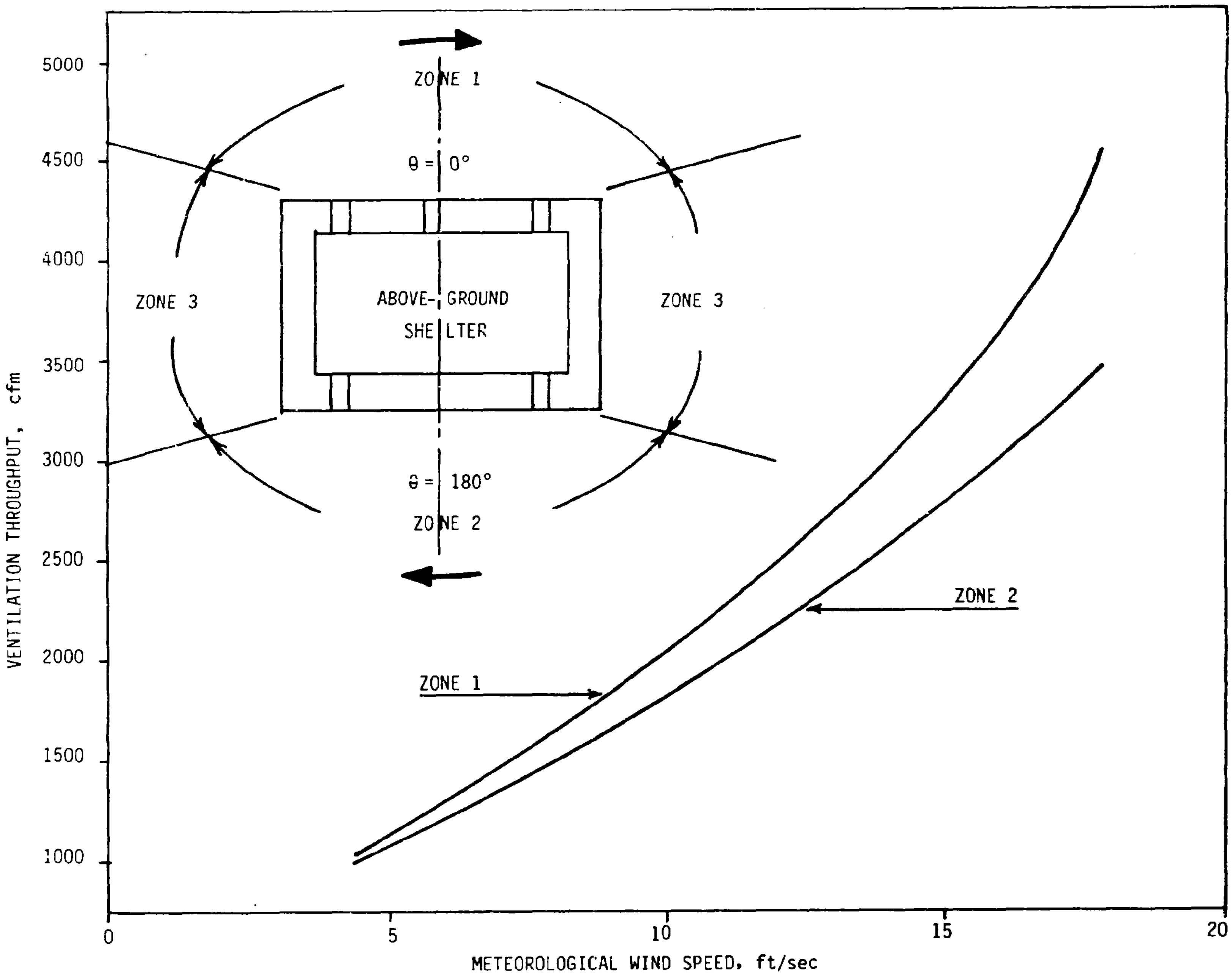
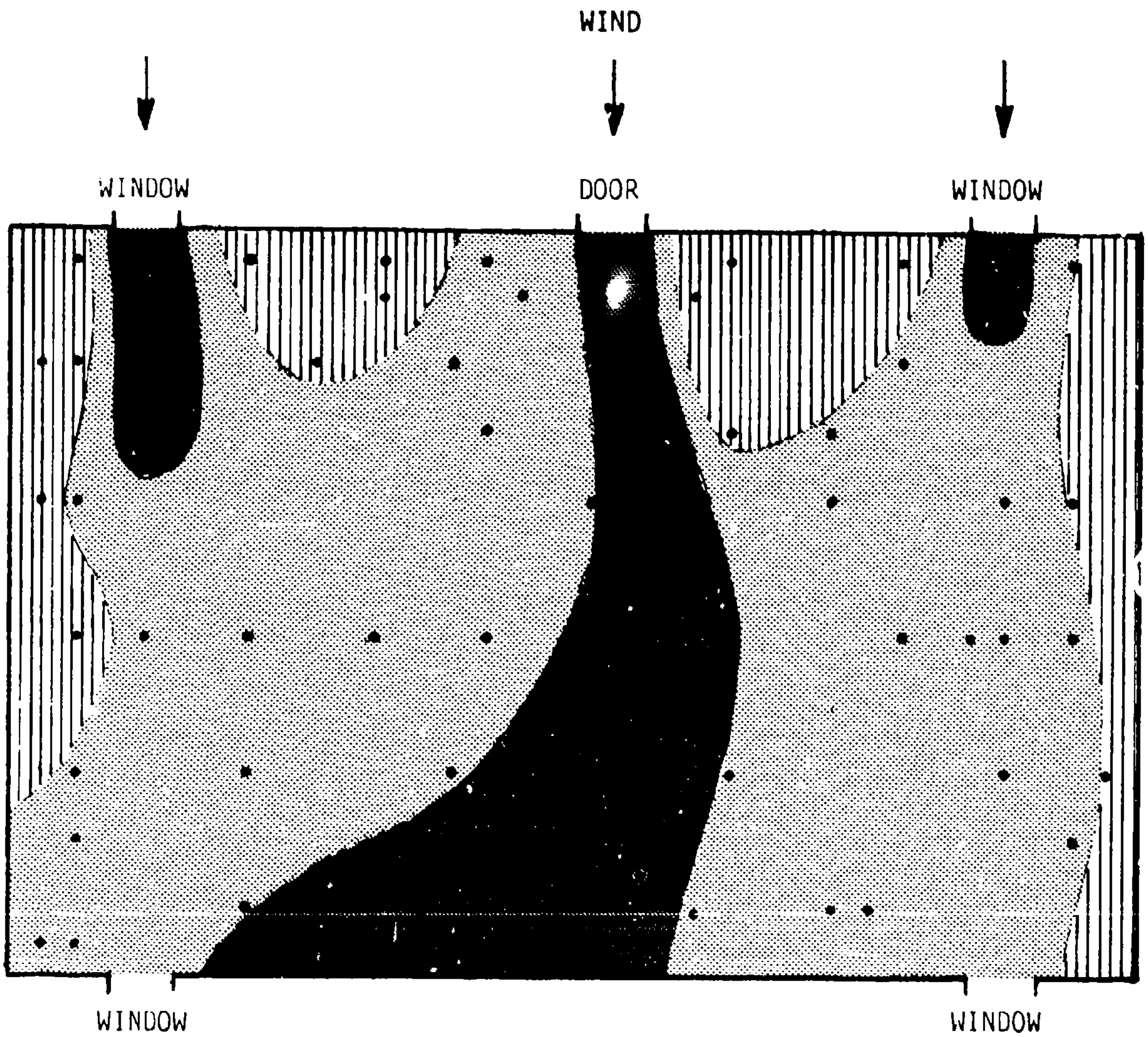


Figure 1 PROJECTED VENTILATION RATES FOR FULL-SCALE SHELTER



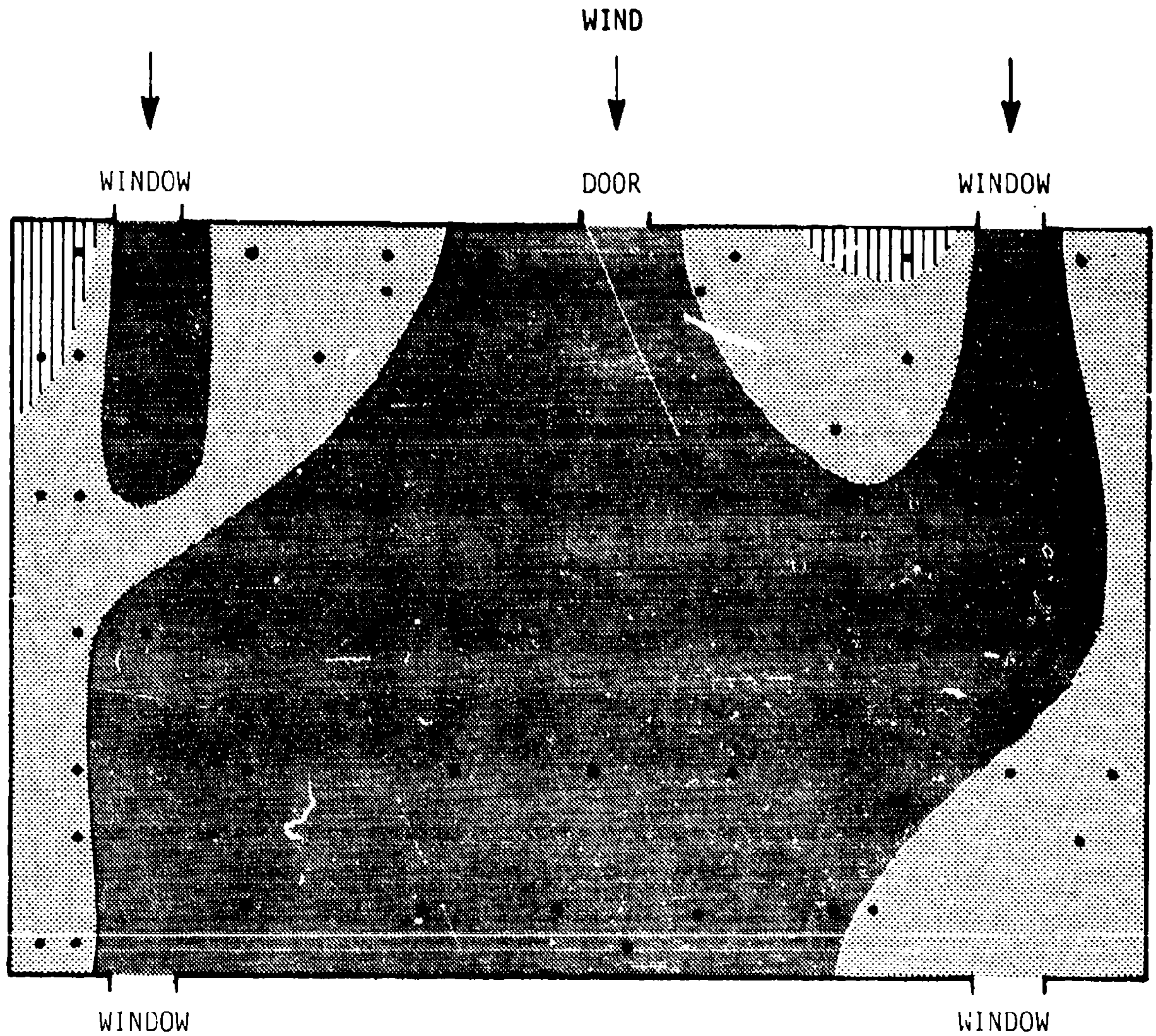
Areas of good ventilation, Temperature drop 11.8°F to 14.6°F.

Areas of moderate ventilation, Temperature drop 9°F to 11.8°F.

Areas of poor ventilation, Temperature drop less than 9°F.

Wind speed = 5.5 fps
Relative wind angle = 0 deg.
Height above floor = 1-5/8 in.

Figure 2 AIR FLOW DISTRIBUTION



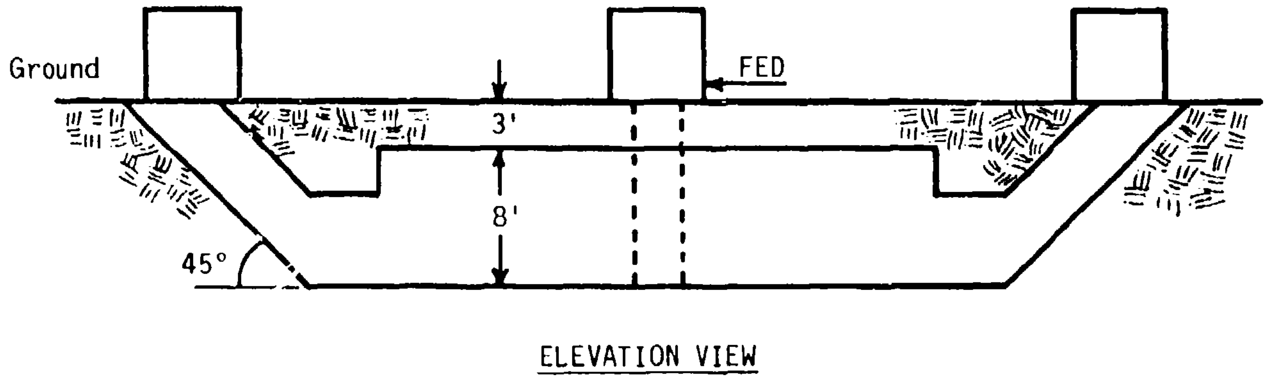
Areas of good ventilation, Temperature drop 11.8°F to 14.6°F.

Areas of moderate ventilation, Temperature drop 9°F to 11.8°F.

Areas of poor ventilation, Temperature drop less than 9°F.

Wind speed = 12.7 fps
Relative wind angle = 0 deg.
Height above floor = 1-5/8 in.

Figure 3 AIR FLOW DISTRIBUTION



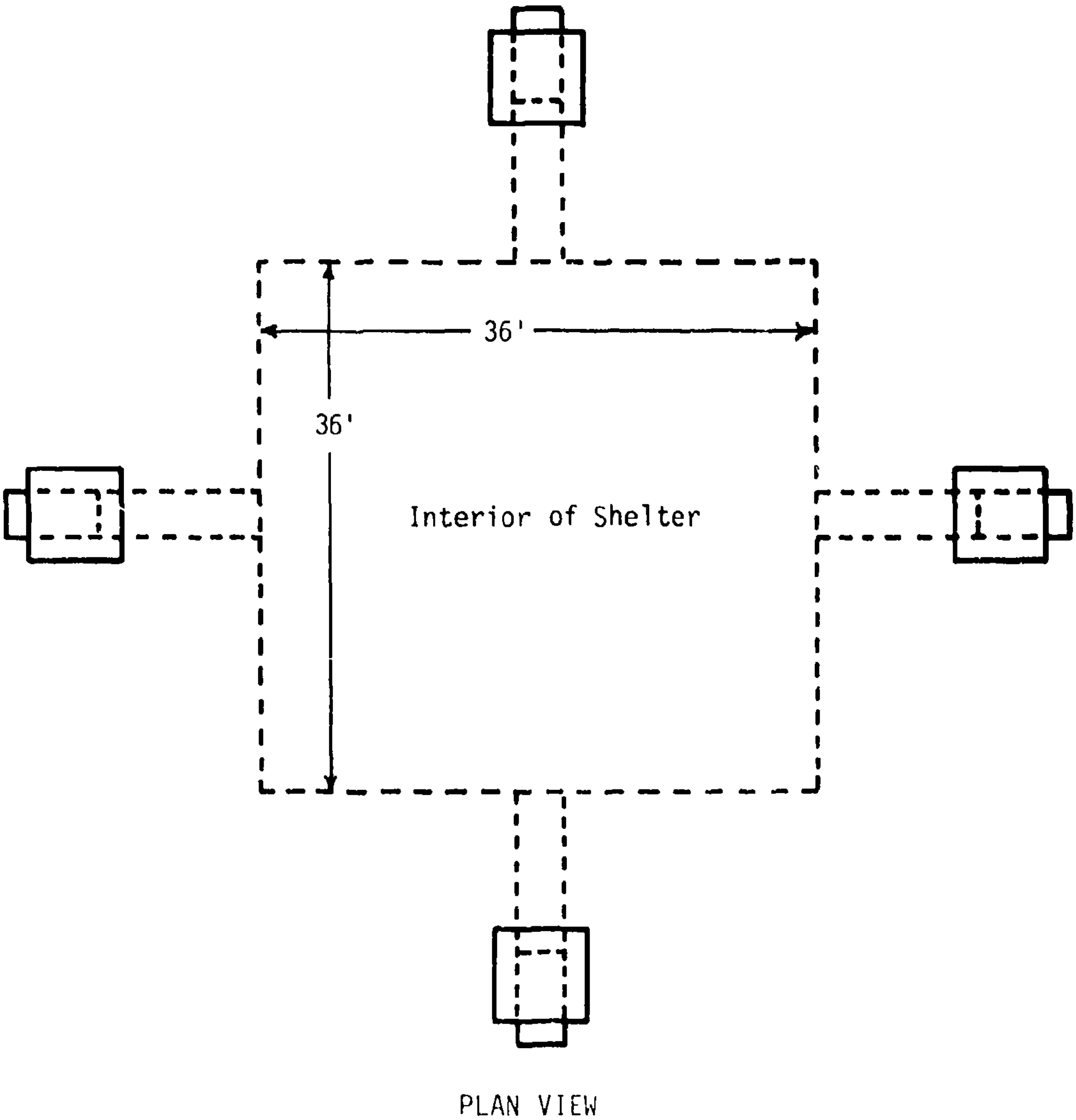


Figure 4 BELOW-GROUND SHELTER WITH 'FED'

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March, 1983

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Washington, D.C. 20472

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PREFACE

GARD, INC. the research and development subsidiary of GATX, has prepared this report for the Federal Emergency Management Agency (FEMA) in Washington, D.C. Mr. Donald Bettge of FEMA served as Project Officer during the entire program.

This report describes the results of the experimental studies that were conducted to aid in the preparation of a methodology to determine the potential of natural ventilation to ventilate upgraded shelters. Scale model tests were conducted using a low speed wind tunnel to obtain correlations between wind velocity and ventilation throughput in an earth-bermed, above-ground shelter. Using a temperature-decay method, air distribution inside the shelter was also analyzed. Expedient "flow enhancement devices" that could be placed at the entrance/exit openings to stairways of below-ground shelters were concepted and some initial tests were made with them. Model tests to evaluate their effectiveness quantitatively and to optimize their design are presently in progress.

Individuals at GARD who participated in this program include:

R. H. Henninger - Project Engineer
Dr. S. F. Fields - Experimental Modeling
Dr. C. K. Krishnakumar - Experimental Modeling
J. B. Koh - Data Reduction

GARD wishes to thank Mr. Bettge and FEMA for the opportunity to have undertaken this study.

Respectfully submitted,

R. H. Henninger

R. H. Henninger, P.E.
Project Engineer

Approved by:

P. A. Saigh

P. A. Saigh, P.E.
Director, Government Programs

ABSTRACT

Scale model tests using a low speed wind tunnel were performed to determine the wind-induced ventilation throughput in an earth-bermed, single-room, above-ground shelter over a wide range of approach wind velocities. Air flow through the wall openings and the interior of the model was traced with neutrally buoyant tracer bubbles and recorded using a movie camera. Volume flow rate through a door or window opening was determined by taking the product of the average bubble velocity, the area of the opening and an experimentally determined area coefficient. Model ventilation throughput values were obtained by adding the air volume flow rates through all the inlet openings and the full-scale values were projected using scaling laws. Air distribution (fresh air mixing) inside the shelter was also analyzed for different approach wind conditions using a temperature-decay method.

A simple design of a Flow Enhancement Device (FED) which could significantly improve wind-induced ventilation in a below-ground shelter was concepted. A scale model of a 100-person, key worker type below-ground shelter was fabricated and preliminary runs were made with it.

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Section 1

INTRODUCTION

1.1 Background

Fallout shelters are used to protect the civilian population from the dangers of a nuclear attack. The occupants may have to stay inside the shelters for extended periods of time without the benefit of electrical power. Providing adequate ventilation to the shelter occupants in those situations has been of primary concern to civil defense authorities.

Ventilation rates of about 3 cubic feet per minute (cfm) per person are known to be sufficient to provide the required oxygen supply and prevent carbon dioxide buildup. However, much higher rates of ventilation are required to protect them from excessive thermal levels inside the shelters. In extreme cases, required ventilation rates could go as high as 50 cfm per person (Ref. 1).

Shelter ventilation can be accomplished by either natural or forced ventilation. Natural ventilation results from thermal effects and wind forces whereas forced ventilation is created by mechanical devices such as pedal ventilators and Kearny pumps. If natural ventilation in a shelter can be predicted with reasonable accuracy, its adequacy/inadequacy based on an accepted thermal comfort level can be assessed. If natural ventilation is found to be inadequate, methods of enhancing it such as providing expedient wall openings should be investigated as the next step, reserving forced ventilation for those situations where natural ventilation enhancement methods are inadequate. In the past, several analytical and experimental studies have been made to assess natural ventilation in full-scale buildings.* However, reliable methods for predicting ventilation throughput and air distribution in buildings and shelters are yet to be established. An up-to-date review of literature relating to natural ventilation and its relation to thermal environments in shelters is given in the following section.

Providing adequate air supply to occupants of below-ground key worker shelters using only natural ventilation is another challenging problem. One

* An exhaustive lising of these studies is given in an earlier study by GARD, Ref. 2.

possible solution to this problem might be the use of easily replaceable flow enhancement devices (FEDs) located near the entrance and exit stairway openings. Properly designed FEDs could help to generate optimal combinations of pressure and wake fields near the entrance and exit openings to maximize the wind-induced air volume flow rate through the shelter. However, the effectiveness of these devices must be established and their design optimized.

1.2 Objectives and Scope

The overall goal of this study program is to obtain a clear understanding of the complex problem of ventilation in above-ground fallout shelters with and without internal partitions and in below-ground key worker shelters so that the ventilation throughput and the air distribution can be predicted and practical recommendations made to improve them. The specific objectives of the present study (Phase I) are the following:

- Establish an empirical correlation between the wind-induced ventilation throughput (cfm) and the approach wind velocity for a basic one-room, above-ground, bermed shelter with an occupant density of 1 person per 10 square feet.
- Analyze and compare the air flow distribution inside the shelter for different wind conditions.
- Establish a test scheme to study wind-induced ventilation in below-ground shelters of the key worker type.

1.3 Review of Literature

Index of Comfort Level

The most widely used index of thermal comfort level is the so-called effective temperature (ET). This parameter combines the effects of dry bulb and wet bulb temperatures and the air movement to provide equal sensations of warmth or cold. A shortcoming of this index is that it overemphasizes the effect of humidity in cooler conditions and underestimates its effect in warm conditions. Further, it does not fully account for air velocity under hot-humid conditions. A refinement of the effective temperature, called the new effective temperature (ET^*), has been recommended by the American Society of Heating, Refrigerating and Air Conditioning Engineers (Ref. 3, Chapter 8). It is described as the dry bulb temperature that gives a fixed physiological strain at 50% relative humidity. Another index that is sometimes mentioned in the literature is the physiological thermal index (PTI) which refers to a fixed physiological state defined by weighing equally the metabolic energy dissipative power that is related to the wetness and temperature of the skin (Ref. 4). This index has yet to find widespread application.

Building Ventilation Models

Extensive experimental and analytical studies of natural ventilation in full-scale above-ground fallout shelters were conducted by the Defense Civil Preparedness Agency (DCPA) in the 1960s. These studies utilized a relationship similar to the one given in the 1977 ASHRAE Handbook of Fundamentals (Ref. 3, Chapter 21).

$$Q = EAV$$

where Q = Air volume flow rate
E = Effectiveness factor
A = Free area of inlets or outlets whichever is smaller
V = Wind speed

The value of the effectiveness factor varies from 0.5 to 0.6 for perpendicular winds and from 0.25 to 0.35 for winds at other angles. When the inlet and outlet areas are not equal, the flow increases in a nonlinear fashion with the area ratio (Figure 12, Chapter 21 of Ref. 3). The ASHRAE model is very crude and gives results that differ considerably from experimental values as indicated by the full-scale tests conducted by DCPA (Ref. 5-8) and the wind tunnel scale model tests done for the Federal Emergency Management Agency (Ref. 2).

Ventilation and Air Distribution

Ventilation throughput and air distribution inside the shelter are both important factors that influence the comfort level of shelter occupants. However, only limited efforts have been made in the past to assess the effects of air distribution on comfort level. In 1965, an experimental study was conducted by the Protective Structures Development Center (PSDC) to analyze the thermal environment in the basement of a 200-person shelter (Ref. 9).

In this study the air flow rate was varied from 3 cfm per person to 27 cfm per person for two different air distribution systems. The PSDC study, which considered effective temperature as the index of thermal comfort, clearly illustrated the influence of air distribution on thermal comfort.

In a study made by the U.S. Army Construction Engineering Research Laboratories (CERL) in 1975 (Ref. 10), temperature distributions inside three different sizes of plywood shelter models were measured. This study attempted to predict thermally induced air flow rates using measured air temperature rises due to heat released by the occupants.

A recent study by the Research Triangle Institute (Ref. 1) investigated the effects of partitions and expedient openings on the air flow patterns inside shelters. Tests were performed at different rates of air flow generated by thermal forces and also by an exhaust fan placed in one of the openings. Point velocities and temperature distributions inside the shelter were measured using thermister probes. However, no attempt was made to correlate these data with the quality of fresh air mixing (air distribution).

Ventilation of below-ground shelters is traditionally considered to be a problem of forced ventilation. Studies in the past have centered around the design, performance analysis and deployment of mechanical ventilating units (Ref. 11-14). Other studies include one on the air distribution in a 200-person below-ground shelter (Ref. 9) and another on the thermally driven ventilation of a small, family size below-ground shelter (Ref. 15).

1.4 Method of Approach

The approach taken to achieve the first of the objectives stated in the previous section was the following:

1. Experimentally determine the air volume flow rates through openings in a geometrically similar scale model of the above-ground shelter for various wind speeds and angles using GARD's low speed wind tunnel. (A description of the wind tunnel is given in the Appendix.)
2. Obtain a correlation between the air volume flow rates obtained and the approach wind speeds and angles.

3. Applying the scaling laws, translate the model air volume flow rates to full-scale values.

In order to determine the model air volume flow rates, the flow visualization technique developed by GARD in a previos study (Ref. 2) was used. This technique involves the tracing and photographic recording of path lines of neutrally buoyant tracer bubbles passing through the model openings and determining the average bubble velocities from these recordings. The air volume flow rate through an opening of the model for a given approach wind condition is then determined by multiplying the average bubble velocity through that opening by its effective through-flow area.* Ventilation throughputs for the model shelter are obtained by adding up the air volume flow rates through all the inlet openings. Ventilation rates for the full-scale shelter are calculated from the model values using appropriate scaling laws.

The technique used to achieve the second objective , i.e., analysis of air distribution inside the shelter, consists of initially filling the interior of the model with warm air and then monitoring the decay of temperature at a sufficient number of well distributed locations due to the ventilating air stream. Locations showing rapid decrease in temperature indentify areas of good ventilation (fresh air mixing) and those with slower decrease in temperature identify areas of relatively poor ventilation.

For ventilation studies of below-ground shelters, a scale model test program somewhat similar to the one described for the above-ground model was considered the best choice (with the model suspended below the Plexiglas turntable of the wind tunnel test section). The scope of Phase I of the study was limited to fabricating the below-ground model, conducting preliminary tests and obtaining initial design parameters for FEDs. Complete tests with the below-ground model will be performed under Phase II.

* The "through-flow area" is defined as the area which, when multiplied by the measured average velocity of the bubbles, gives the actual volume flow rate. The ratio of through-flow area to the geometric area of an opening is termed its "area coefficient, A_C".

Section 2

BASELINE VENTILATION RATES FOR ABOVE-GROUND SHELTER

2.1 Shelter Geometry

The configuration of the basic one-room above-ground bermed shelter* studied in the present program is shown in Figure 2.1. The 48 feet x 32 feet x 12 feet shelter has two windows and a door on one long wall and two identical windows on the opposite long wall. There are no openings on either of the shorter side walls. For convenience, the windows are labeled 1 through 4 as shown in the figure. The configuration is basically similar to shelter model 030 described in Reference 1. However, the present model differs from the one referenced in two aspects:

1. The present model is covered with a simulated earth berm whereas the referenced model had none.
2. A ceiling height of 12 feet was used as opposed to 8 feet in the referenced model.

2.2 Scaling Laws

The basic requirement in model testing is dynamic similarity between the full-scale and model systems. To achieve dynamic similarity the following must be satisfied:

(i) geometric similarity between the model and full-scale shelters

(ii) large enough values of Reynolds numbers based on tunnel floor boundary layer thickness and length dimensions of the model to insure good turbulent mixing in the boundary layers

(iii) similarity in the velocity profiles of the approach wind boundary layers

(iv) equality of the ratio of building height to approach wind boundary layer thickness.

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* This particular shelter configuration was selected after discussions with FEMA personnel.

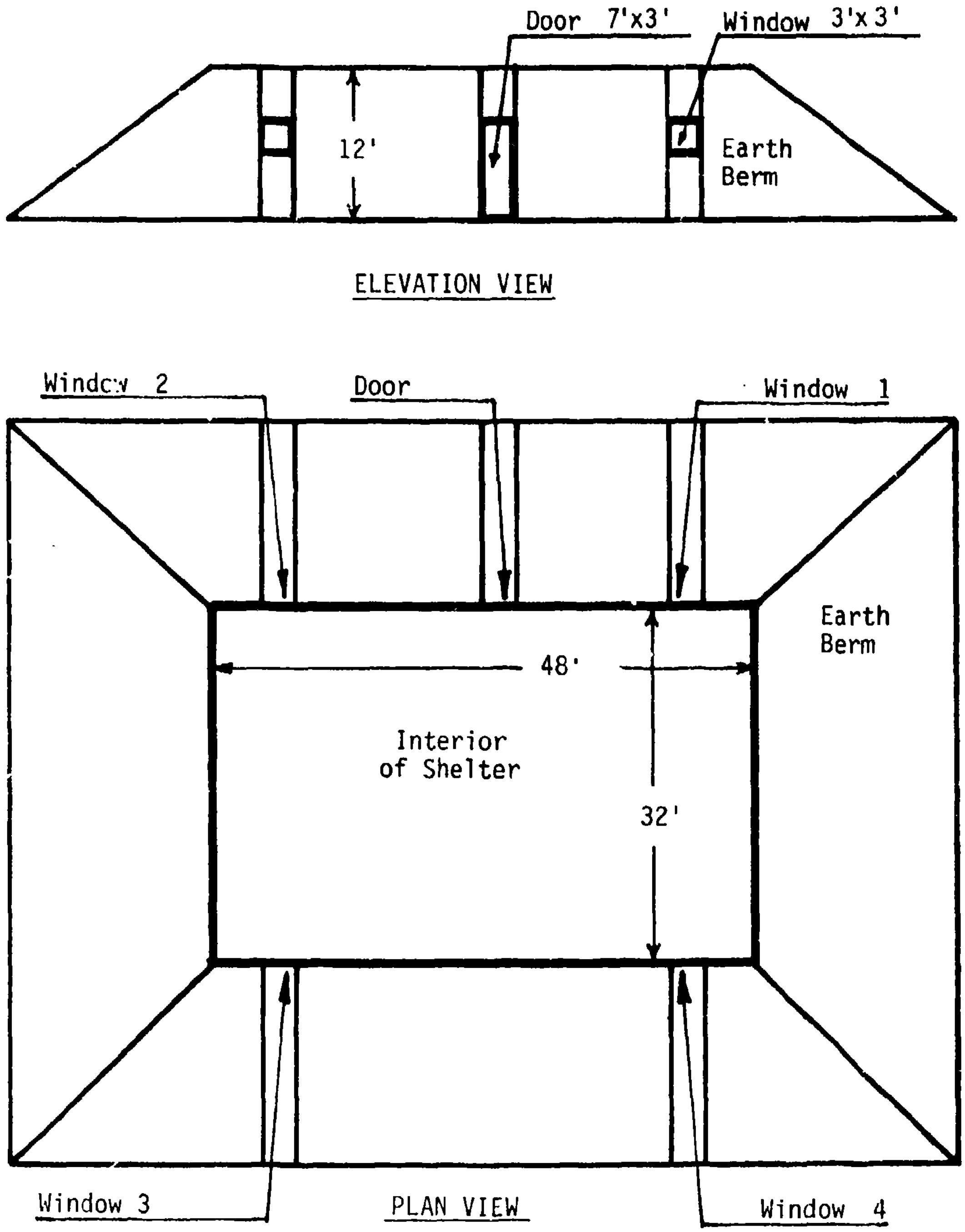

Figure 2.1 ABOVE-GROUND UPGRADED SHELTER

Additionally, the model should be small enough to insure that tunnel blockage effects and boundary layer interference effects are insignificant. On the other hand, the model should not be too small to render accurate measurements difficult or to amplify errors due to imperfections in model fabrication. A detailed discussion of scaling considerations is given in the previous GARD study (Ref. 2).

2.3 Design and Fabrication of Model

A length scale of 1:36 (model: full-scale) was found to be a good choice for satisfying the scaling requirements. The geometrically similar shelter model was fabricated to this scale using plywood, aluminum and tempered glass sheets (Figure 2.2). The door and window openings were machined out of the aluminum sheets which formed two of the interior walls of the shelter model. The other two interior walls were made of tempered, transparent glass sheets (Figure 2.3). Four 250-watt light bulbs were located inside the hollow wedge shaped spaces formed by the glass walls and the simulated earth berms (Figure 2.4). These lights provided sufficient intensity to illuminate the interior flow paths traced by the bubbles. A thin transparent plastic sheet scribed with lines one-quarter inch apart across the shelter openings was used as the base of the model. Upright cylindrical blocks of aluminum, ½-inch in diameter and 1-inch long, were used to simulate occupants in a sitting posture (Figure 2.5).

2.4 Wind Tunnel Calibration

Before placing the shelter model in the test area, several test runs* were made to calibrate the tunnel as described in GARD's earlier study (Ref. 2). These tests established an approach wind velocity profile conforming to a power law distribution with an exponent of $\frac{1}{4.5}$. This is typical of wind velocity profiles on suburban land with short bushes. The boundary layer thickness was approximately 18 inches (Figure 2.6), giving a value of 4.5 for the ratio of boundary layer thickness to building height.

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* A description of the wind tunnel is given in the Appendix.

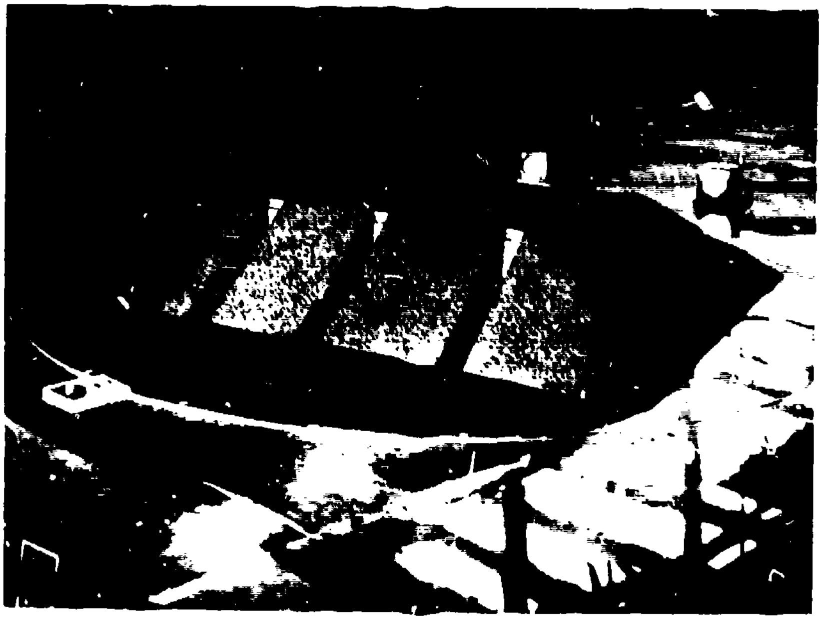

Figure 2.2 ABOVE-GROUND SHELTER IN THE TUNNEL TEST SECTION

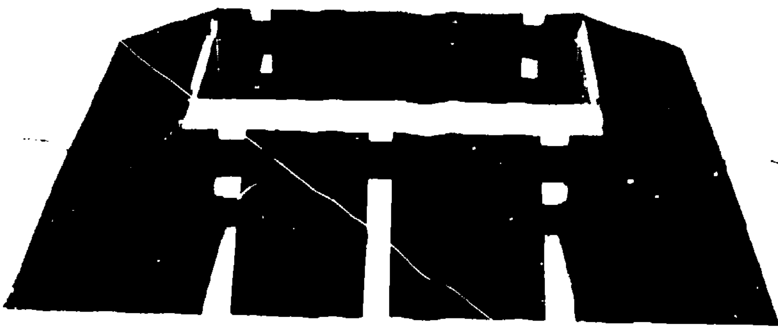

Figure 2.3 ABOVE-GROUND SHELTER WITH ROOF REMOVED

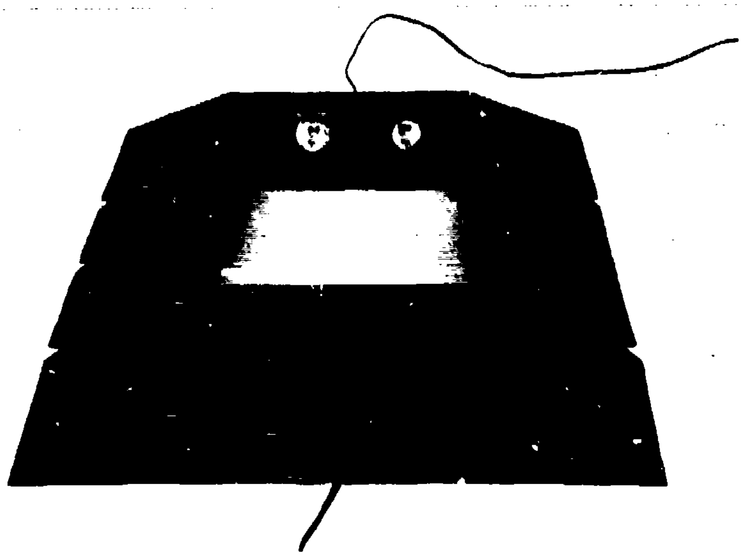

Figure 2.4 ABOVE-GROUND SHELTER SHOWING INTERNAL LIGHTING THROUGH BERMS

Figure 2.5 ABOVE-GROUND SHELTER WITH SIMULATED OCCUPANTS

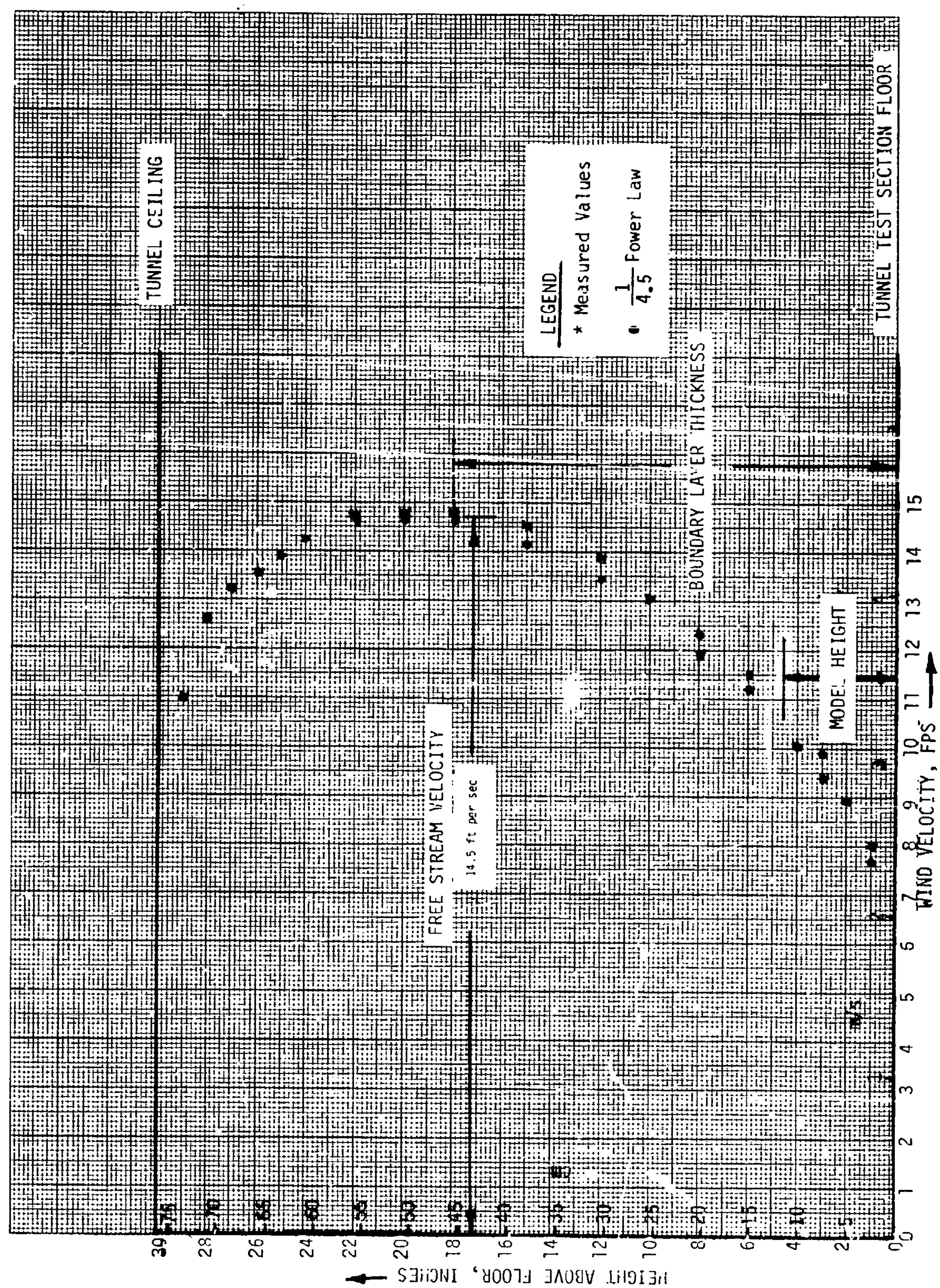

Figure 2.6 BOUNDARY LAYER VELOCITY PROFILE

2.5 Model Tests for Establishing Baseline Ventilation Rates

A series of baseline tests were conducted at twelve values of relative wind angles (see Figure 2.7) and four values of wind speed at each of the angles. Relative wind angles were varied by rotating the Plexiglas turntable which carried the model. Wind speeds were varied by adjusting the variable speed frequency controller which regulates the rotational speed of the drive motor of the wind tunnel blower. The following section describes the procedure used for this series of tests.

2.6 Test Procedure

The shelter model was placed on the turntable and aligned at the zero degree reference position. The turntable was then rotated so that the diameter passing through the desired angle mark on the turntable aligned with a reference mark on the tunnel floor. This set the value of the relative wind angle. The pitot-static probes that measure the wind velocity were raised to about 20 inches above the tunnel floor to be in the free stream zone. Five 250-watt lights (effective diameter 2 inches) were positioned approximately two feet away from the model with their beams directed to illuminate the floor area and the scribed lines immediately outside of the shelter wall openings.

The mirror placed under the turntable was then adjusted to reflect the plan view of the interior of the model for photographic recording (Figure 2.8). The movie camera was stationed about 4 feet from the center of the mirror and focused on the mirror image of the model's interior. Helium and compressed air supplies to the SAI bubble generator and the control knobs of the console were adjusted to release neutrally bouyant bubbles (~ 1/8-inch diameter) through the release tubes at the desired rates. Locations of the bubble release tubes upstream of the wall openings were adjusted to achieve proper bubble flow through each of the windward openings. The 250-watt lights placed inside the model berms as well as those outside the model were all illuminated and the movie camera turned on for about 15 seconds at a speed of 120 frames per second. The lights and bubble generator were then switched off and the blower speed setting adjusted for another wind speed. The test was repeated for the new wind speed after conditions became steady. For each orientation of the model, bubble flow was filmed at 4 different wind speeds. Once this

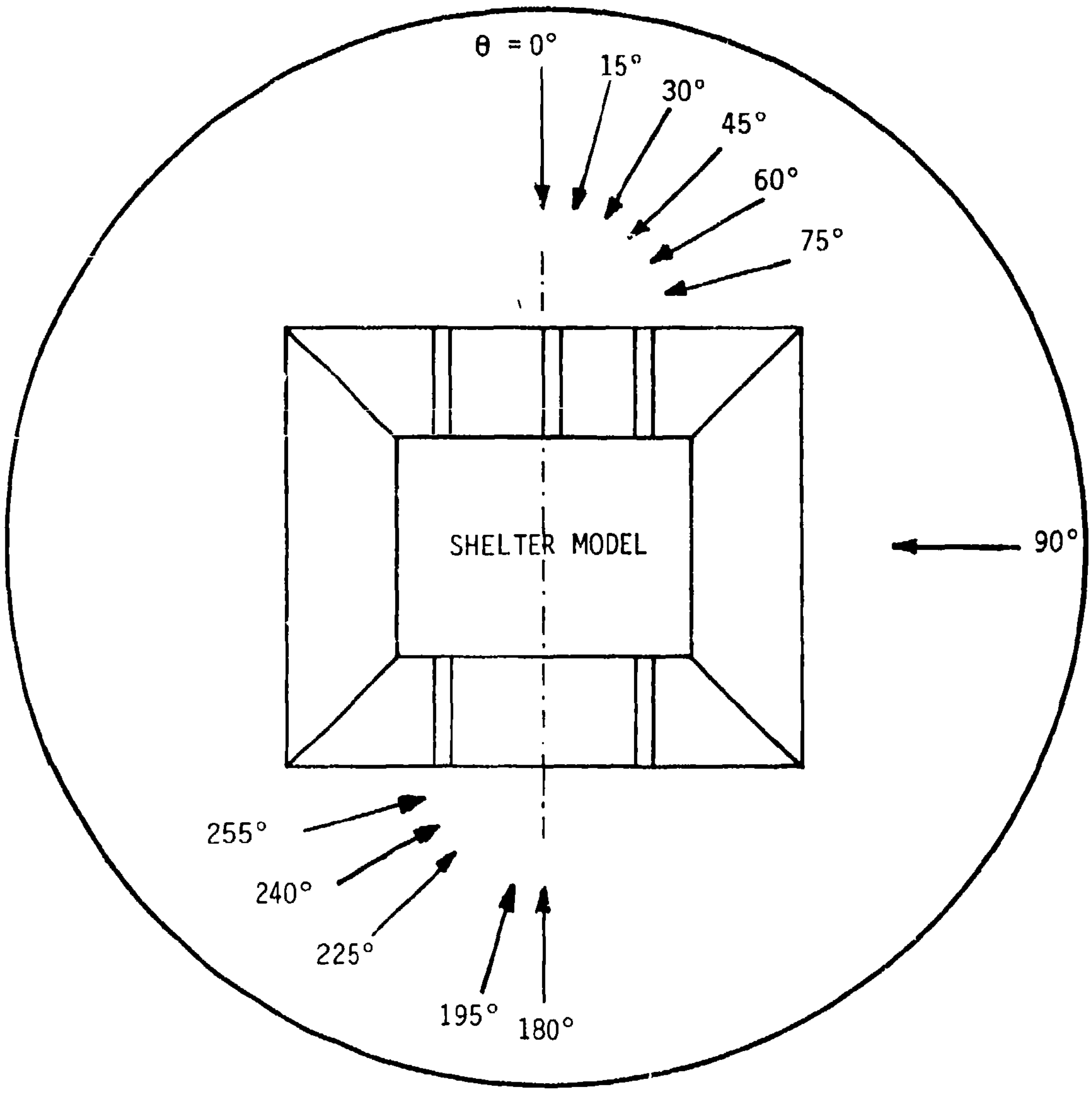

Figure 2.7 VENTILATION THROUGHPUT OF ABOVE-GROUND MODEL
- WIND ANGLES TESTED

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Figure 2.8 TEST SETUP FOR RECORDING OF FLOW TRACERS FOR DETERMINING VENTILATION THROUGHPUT IN ABOVE-GROUND SHELTER MODEL

was completed, the turntable was rotated to set a different wind angle. The positions of the exterior lights and the bubble release tubes were again adjusted and filming of the tracer bubbles for the new wind angle repeated.

In all, 48 tests, i.e., twelve values of the relative wind angle θ and four values of the wind speed at each of the angles, were carried out under this test series. However, for θ equal to 90° satisfactory bubble flow through the openings could not be realized without locating the bubble release tubes right next to the edge of the berm. At such close proximity, the bubble streams appeared to disturb the pressure fields in front of the openings significantly. Therefore, bubble path lines were not recorded for this value of the relative wind angle. However, qualitative estimates of air flow through the model were made by generating cigarette smoke at various locations on either side of each opening.

2.7 Data Reduction

The movie films were projected frame by frame and the bubble velocity normal to an opening was determined from the known distance between the markings across the opening and the camera speed. The average velocity of twenty bubbles was taken to establish the average flow velocity for the "through-flow area" of the opening. Table 2.1 shows the average bubble flow velocities for each of the wall openings over the values of relative wind angle and wind speed tested.

2.8 Determination of Area Coefficients

The area coefficient of an opening was defined in Section 1.4 as,

$$A_c = \frac{\text{bubble through-flow area}}{\text{geometric area of opening}}$$

$$= \frac{\text{bubble through-flow area x average bubble velocity}}{\text{geometric area x average bubble velocity}}$$

$$= \frac{\text{actual volume flow rate}}{\text{geometric area x average bubble velocity}}$$

Values of area coefficients were determined for each of the windward openings for a variety of wind conditions using the test setup shown in Figure 2.9.

Table 2.1 BUBBLE VELOCITIES THROUGH INLET OPENINGS OF MODEL

OPENING	Free Stream Wind Speed (ft/sec)	Measured average bubble velocities (ft/sec) through inlet openings of model at relative wind angle of										
		0°	15°	30°	45°	60°	75°	180°	195°	225°	240°	255°
Window 1	5.2	3.39	2.54	3.26	2.28	2.02	2.94	Act as exit openings at these angles				
	8.4	—	3.34	3.38	2.87	2.94	3.31					
	13.4	4.85	3.67	3.67	3.26	3.85	3.75					
	19.8	7.68	6.98	5.10	5.07	4.84	4.34					
Window 2	5.2	3.50	1.91	3.85	2.61	2.94	3.12					
	8.4	—	2.53	3.49	3.38	2.28	3.67					
	13.4	4.63	3.56	4.73	3.45	3.16	3.23					
	19.8	7.23	4.84	5.69	4.96	3.23	4.40					
Door	5.2	1.98	2.50	4.63	3.38	3.12	5.02					
	8.4	—	3.49	5.69	4.34	4.63	5.14					
	13.4	4.63	3.67	5.90	4.92	4.34	5.87					
	19.8	7.34	7.23	6.79	6.98	5.22	5.14					
Window 3	5.2	Act as exit openings at these angles						3.49	3.85	4.52	2.72	4.34
	8.4							4.44	4.52	4.08	3.38	3.16
	13.4							5.76	6.60	4.84	4.63	3.85
	19.8							8.07	8.00	6.68	6.05	5.66
Window 4	5.2							3.12	4.34	4.08	3.38	3.16
	8.4							4.63	5.54	4.92	4.11	3.20
	13.4							5.76	6.86	6.60	5.43	4.44
	19.8							7.96	9.72	7.37	7.12	5.36

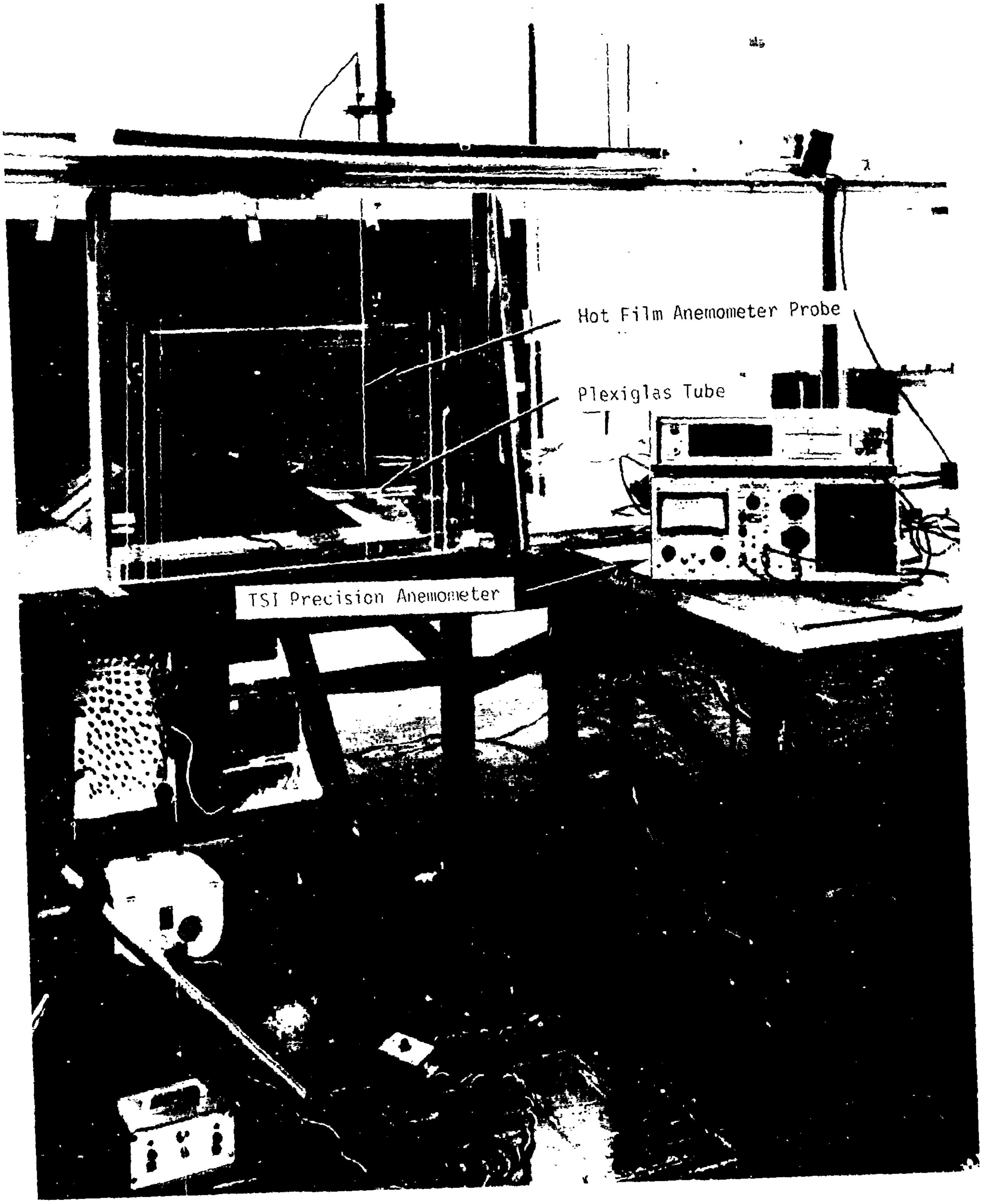


Figure 2.9 TEST SETUP FOR DETERMINING AREA COEFFICIENT OF OPENINGS

To determine the actual volume flow rate through a windward opening, a 3/4-inch diameter clear Plexiglas tube (16-inches long) was attached to one of the leeward openings and all other openings were sealed. The leading edge of the Plexiglas tube was made flush with the inner surface of the shelter wall. The model was placed on the turntable in the reference position and the turntable rotated to set the desired wind angle. A TSI precision hot-film anemometer probe attached to the tunnel ceiling was positioned to enter the Plexiglas tube at a section 12 inches from the leading edge. The probe position was then adjusted to give the centerline air velocity in the tube. The wind tunnel blower and the counterjet were set to generate the desired approach wind. Once conditions became steady, the anemometer readings were recorded. The mean of 40 readings over a period of 80 seconds was taken as the average velocity corresponding to the probe position. By varying the radial location of the probe sensor in the tube, the velocity profile at that cross section was obtained. Knowing the velocity profile, the ratio of the cross-sectional average velocity to the centerline velocity was determined. This was repeated at three different wind speeds over the range of 5 fps to 20 fps. This ratio varied between 0.48 and 0.82 over the range of wind speeds tested.

Next, the actual air volume flow rate through each of the individual windward openings was determined at relative wind angles of 0°, 30°, 60°, 180° and 240° and at wind speeds of 5.7 fps, 9.6 fps and 19.6 fps at each value of the wind angle. Only the centerline velocity in the tube was measured for each case. Using the measured velocity ratio with the average velocity determined earlier and the cross-sectional area of the tube, the actual volume flow rate was calculated.

Next, the average bubble velocities through the openings corresponding to these measured actual air flow rates were determined. This was done by photographing the bubble path lines through the opening with the movie camera and then averaging the velocities of 20 bubbles as explained earlier. Before releasing the bubbles, the anemometer probe was moved away from the bubble paths to eliminate the possibility of the hot-film sensor being contaminated by contact with the bubbles. Values of the area coefficients were calculated by the relation,

$$A_c = \frac{\text{actual air volume flow rate through Plexiglas tube}}{\text{area of opening x average bubble velocity through it}}$$

Table 2.2 presents the values of A_c for the five wall openings.

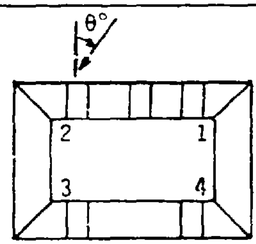
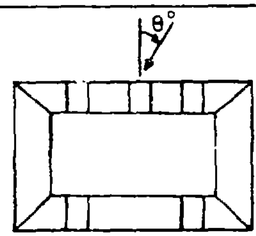
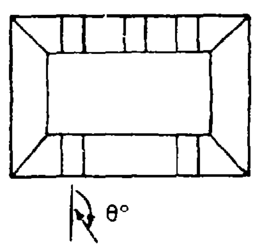
2.9 Results and Discussions

Table 2.3 presents the experimentally measured ventilation air volume flow rates for the modelled above-ground shelter for eleven values of the relative wind angle and four values of wind speed. Presented also are the air volume flow rates through each individual opening on the windward side. The air volume flow rate through an opening for a given wind condition was obtained by multiplying the average measured bubble velocity through the opening by its geometric area and the area coefficient. The model ventilation throughput was then calculated as the sum of the air volume flow rates through all the windward openings.

The variation of model ventilation througnput versus wind speed for the various wind angles is graphically illustrated in Figures 2.10 and 2.11. Figure 2.10 shows test results for values of relative wind angle ranging from 0° to 75° and Figure 2.11 shows results for relative wind angle ranging from 180° to 255°. The shaded areas in each figure show the spread of ventilation throughput values over the range of wind angles tested. It is clearly seen that the ventilation throughput is primarily a function of the wind speed.

Projected mean values of ventilation throughput for the full-scale shelter as derived from the scaled model results are shown in Figure 2.12. Values of full-scale ventilation throughput were obtained by scaling up those of the model by the volume rate scale of 1:1296 (model:full-scale). Since the shelter geometry is nearly symmetrical about the 0° - 180° axis, the ventilation throughput versus wind speed relations are expected to be the same on either side of this axis. For values of relative wind angle in the immediate neighborhood of 90° and 270°, the ventilation throughputs would be slightly less than those in Zone 2 of Figure 2.12. This projection is based on qualitative estimates of the model air volume flow rates made from visual observations of cigarette smoke and bubble tracers.

TABLE 2.2 VALUES OF AREA COEFFICIENTS (A_c) FOR MODEL INLET OPENINGS

Wind Speed, ft/sec		5.2			8.4			13.4			19.8		
Relative Wind Angle, θ°		0°,15° 30°	45° 75°	60°	0°,15° 30°	45° 75°	60°	0°,15° 30°	45° 75°	60°	0°,15° 30°	45° 75°	60°
	A_c Windows 1 & 2	0.17	0.19	0.21	0.20	0.25	0.29	0.25	0.34	0.43	0.32	0.44	0.56
	A_c Door	0.12	0.12	0.12	0.16	0.16	0.16	0.22	0.22	0.22	0.30	0.30	0.30
Relative Wind Angle, θ°		180° 195°	225° 255°	240°	180° 195°	225° 255°	240°	180° 195°	225° 255°	240°	180° 195°	225° 255°	240°
	A_c Windows 3 & 4	0.23	0.25	0.30	0.27	0.31	0.37	0.33	0.39	0.47	0.40	0.49	0.59

Note: Values at 0°, 30°, 60°, 120° and 180° were measured. Values at other angles were interpolated.

Table 2.3 MODEL VENTILATION THROUGHPUT

Opening	Free Stream Wind Speed ft/sec	Air Volume Flow Rate (cfm) At Relative Wind Angles of 0°	15°	30°	45°	60°	75°	180°	195°	225°	240°	255°
Window 1	5.2	.24	.18	.23	.18	.18	.23					
	8.4	—	.28	.29	.30	.36	.34					
	13.4	.50	.38	.38	.46	.68	.53					
	19.8	1.02	.93	.68	.94	1.13	.80					
Window 2	5.2	.24	.14	.27	.21	.26	.24					
	8.4	—	.21	.30	.35	.28	.38					
	13.4	.48	.37	.49	.49	.56	.46					
	19.8	.96	.65	.76	.92	.75	.81					
Door	5.2	.22	.28	.52	.38	.35	.56					
	8.4	—	.54	.88	.67	.72	.80					
	13.4	1.00	.79	1.27	1.06	.93	1.26					
	19.8	2.15	2.11	1.98	2.04	1.53	1.50					
Model Ventilation Throughput (cfm)	5.2	.70	.60	1.02	.77	.79	1.03					
	8.4	—	1.03	1.47	1.32	1.36	1.52					
	13.4	1.98	1.54	2.14	2.01	2.50	2.25					
	19.8	4.13	3.69	3.42	3.90	3.41	3.11					
Window 3	5.2							.33	.37	.47	.34	.45
	8.4							.49	.50	.51	.52	.41
	13.4							.79	.90	.79	.91	.63
	19.8							1.34	1.33	1.36	1.50	1.15
Window 4	5.2							.30	.42	.42	.42	.33
	8.4							.51	.61	.64	.64	.41
	13.4							.79	.94	1.07	1.06	.72
	19.8							1.32	1.61	1.50	1.76	1.09
Model Ventilation Throughput (cfm)	5.2							.63	.79	.89	.76	.78
	8.4							1.00	1.11	1.15	1.16	.82
	13.4							1.58	1.84	1.86	1.97	1.35
	19.8							2.66	2.94	2.86	3.26	2.24

Model ventilation throughput is obtained as the sum of air volume flow rates through all the windward openings; namely Window 1, Window 2, and the door.

Model ventilation throughput is obtained as the sum of air volume flor rates through all the windward openings, namely Window 3 and Window 4

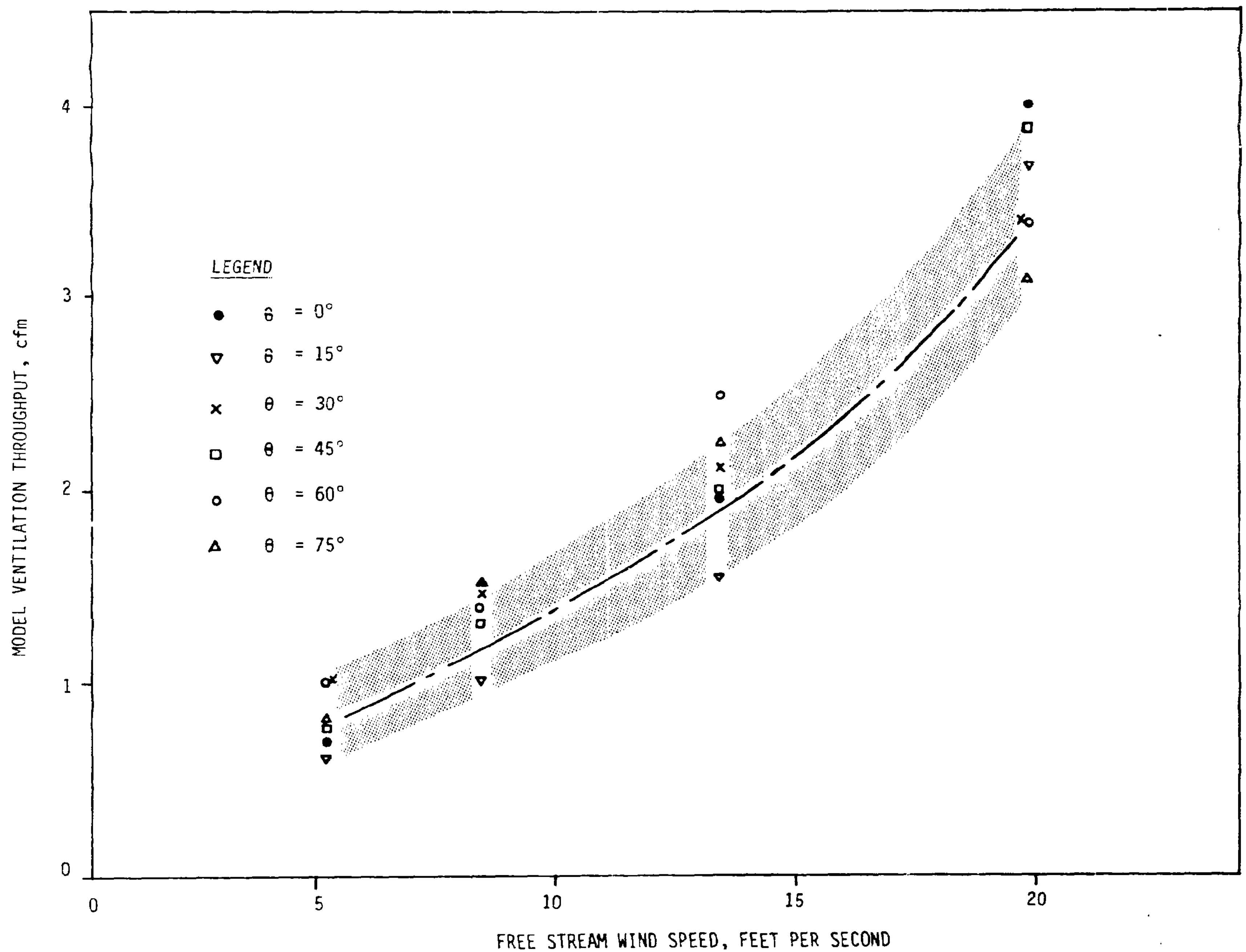


Figure 2-10 VENTILATION RATES FOR ABOVE-GROUND SHELTER MODEL

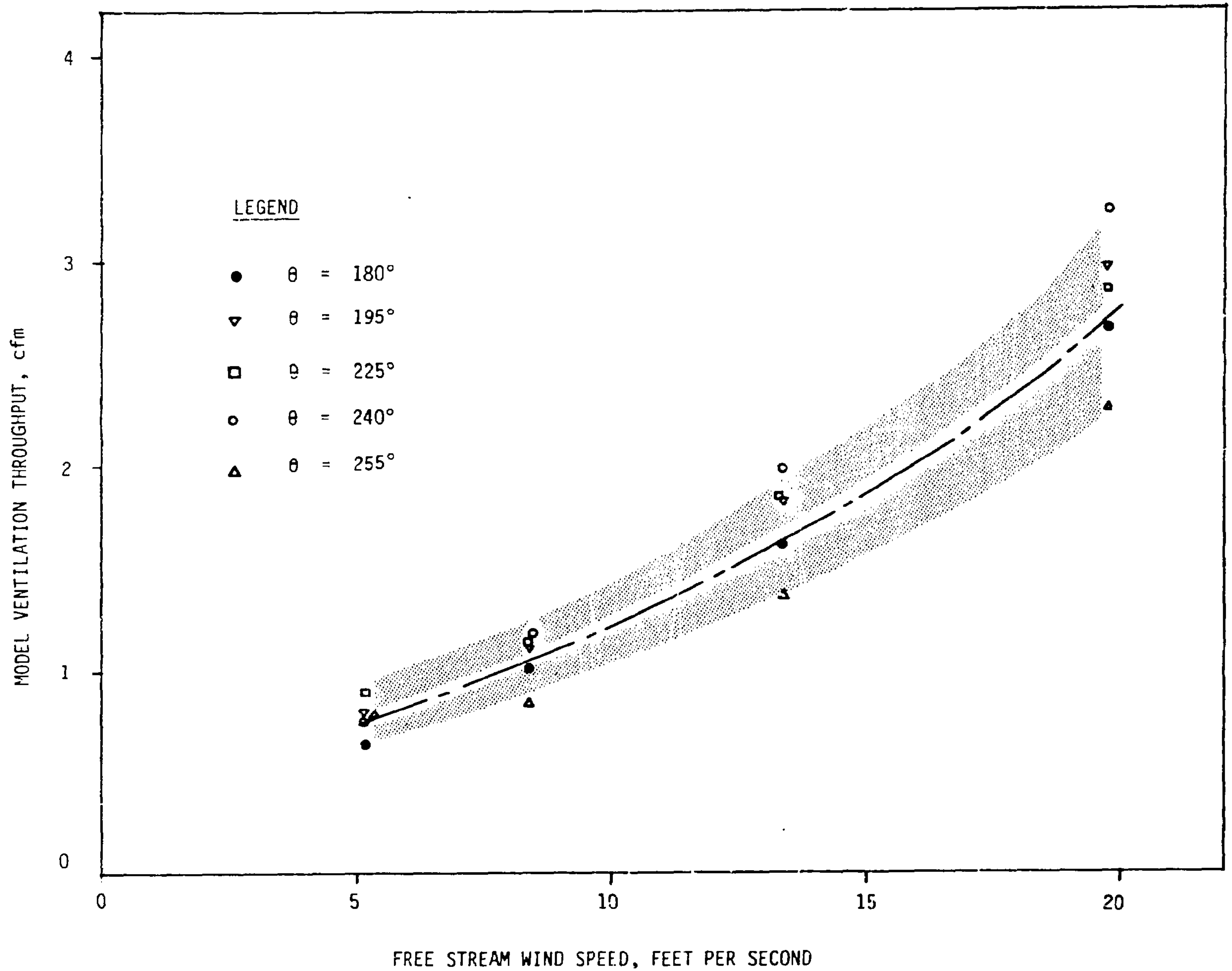


Figure 2.11 VENTILATION RATES FOR ABOVE-GROUND SHELTER MODEL

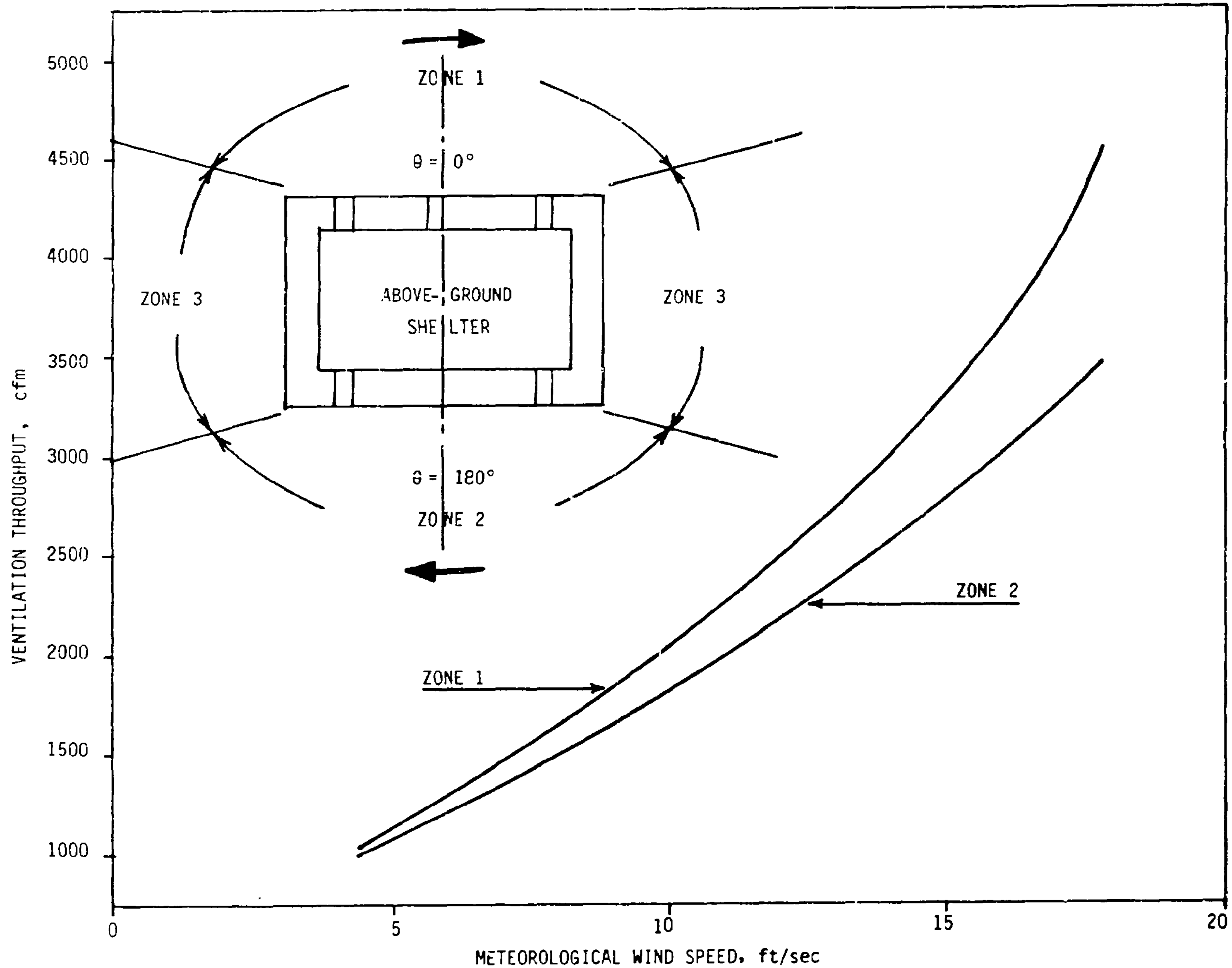


Figure 2.12 PROJECTED VENTILATION RATES FOR FULL-SCALE SHELTER

Several important observations can be made from these results regarding wind-induced ventilation throughput (Q) for the bermed, above-ground shelter studied. A listing and discussion of these observations follows:

1. Ventilation throughput (Q) is primarily a function of the wind speed (V). In the low wind speed range tested, the slope of the ventilation throughput versus wind speed curve ($\frac{dQ}{dV}$) increases with wind speed. This is due to the changing patterns of positive pressure fields near the windward openings and negative pressure fields behind the leeward openings with changes in wind speed. In the range of wind speeds tested, the changes in pressure fields in the vicinity of openings cause the value of the area coefficient to increase with increasing wind speed.

   The 1977 ASHRAE Handbook of Fundamentals (Ref. 3) and the previous GARD study (Ref. 2) suggest a linear relation between ventilation throughput and wind speed. However, it should be noted that the ASHRAE formulation relates to unbermed buildings and the results of the latter were based on an assumed constant value of unity for area coefficients of the openings. (The value of unity is the theoretical upper limit for area coefficient.) Althouth the importance of area coefficient was clearly illustrated in the GARD study, values of area coefficients for the openings were not evaluated. The results of this study now indicate that the ventilation rates reported in the previous study were overestimated due to the assumption of a 1.0 area coefficient.

2. For shelter orientations at which the wall with larger opening area is on the windward side, the ventilation throughput is slightly higher than for cases in which it is on the leeward side. The differences in ventilation throughput are practically insignificant at low wind speeds (about 6% to 7% at a wind speed of 5 feet per second), but they become somewhat significant at higher wind speeds (17% to 18% at a wind speed of 20 feet per second).

3. Dependence of ventilation throughput (Q) on relative wind angle is very weak. For relative wind angles varying from 315° to 75° (wall with larger opening area on windward side, Zone 1 of Figure 2.12), the ventilation throughput is practically independent of wind angle.

   Similarly for θ varying from 105° to 255° (wall with larger opening area on leeward side, Zone 2 of Figure 2.12), the ventilation throughput remains independent of wind angle, although its value is somewhat lower than in Zone 1. Ventilation throughput for relative wind angles very close to 90° and 270°, appears to be slightly below that in Zone 2.

Section 3

AIR FLOW DISTRIBUTION IN ABOVE-GROUND SHELTERS

The estimated occupation periods for shelters vary from several days to several weeks. The level of comfort experienced by the occupants of a shelter is very much dependent upon the air movement patterns within the shelter which create good mixing of ventilation air and shelter air. The model tests described in this section provide qualitative information on the extent of fresh air mixing in different areas of the above-ground shelter described in Section 2 for wind speeds of 12.7 fps and 5.5 fps at relative wind angles of 0° and 45°.

The technique used in these tests consisted of initially filling the interior of the model with warm air and then monitoring the decay of temperature at a sufficient number of well distributed locations due to the ventilating air stream. Areas of good ventilation are identified by locations of rapid decreases in temperature and those of relatively poor ventilation are identified by locations of slower decreases in temperature.

3.1 Model Preparation

The ceiling of the model was removed and grid lines were drawn on its upper face at half inch intervals. Fifty three grid points were selected for introducing thermocouple leads. Shelter areas that appeared to be transition zones between good and poor air mixing received higher concentrations of thermocouples. Holes about 1/8-inch diameter were drilled through the ceiling plate at these selected locations and were numbered 1 through 53. Type T fast response thermocouple leads connected to a 32-channel data logger were mounted in 27 of these holes with the wires protruding 2-3/8 inches below the underside of the ceiling. (This corresponded to an elevation of 1-5/8 inches above the floor.) A sample arrangement is shown in Figures 3.1 and 3.2. The remaining 26 holes and the annular gaps around the lead wires were sealed with tape. The turntable with the model on it was positioned for a desired wind angle. After insuring that the thermocouple tips were all at the same level and the wires were perpendicular to the plane of the ceiling, the

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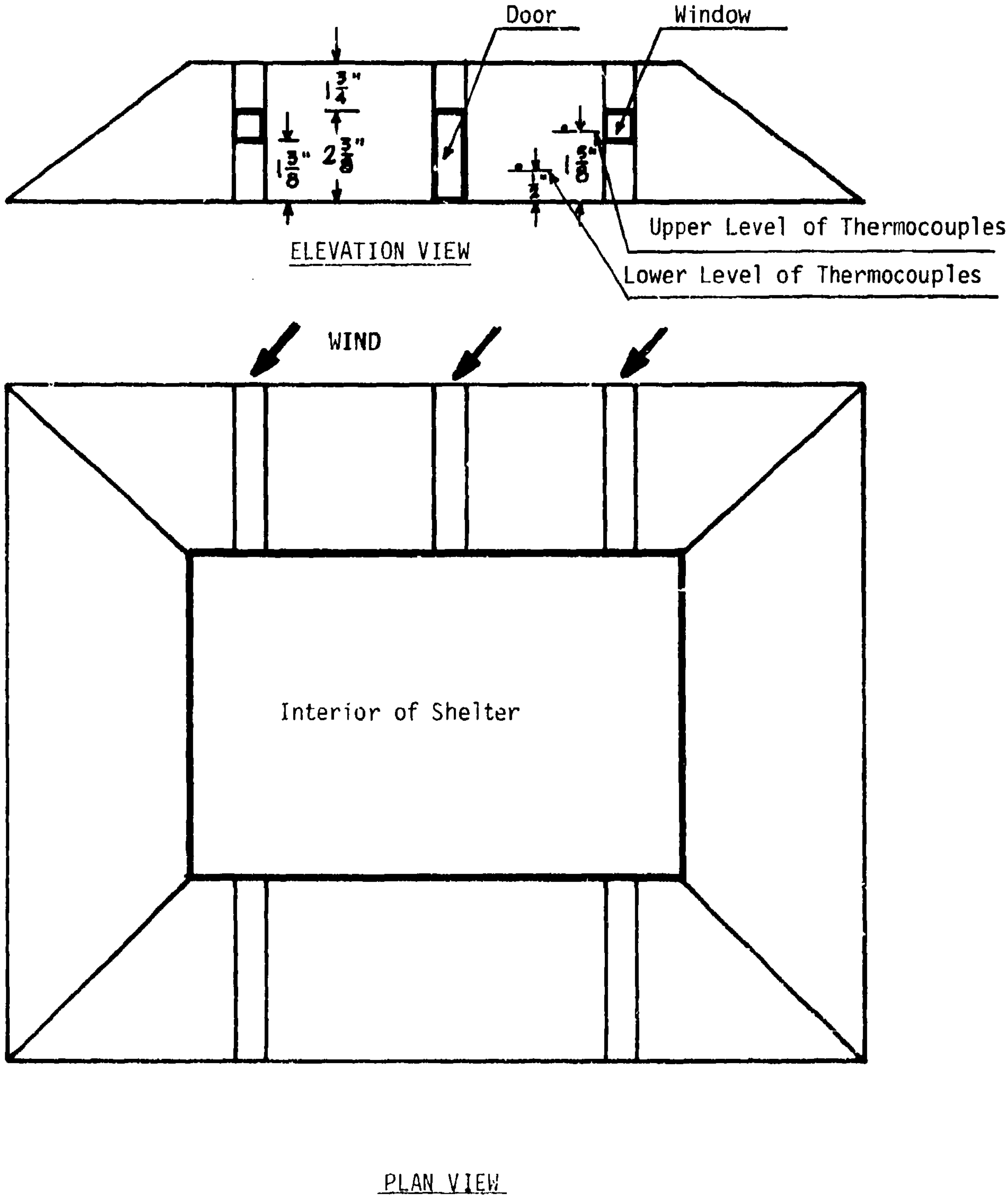

Figure 3.1 ABOVE-GROUND SHELTER MODEL SHOWING LEVELS OF THERMOCOUPLE LOCATIONS

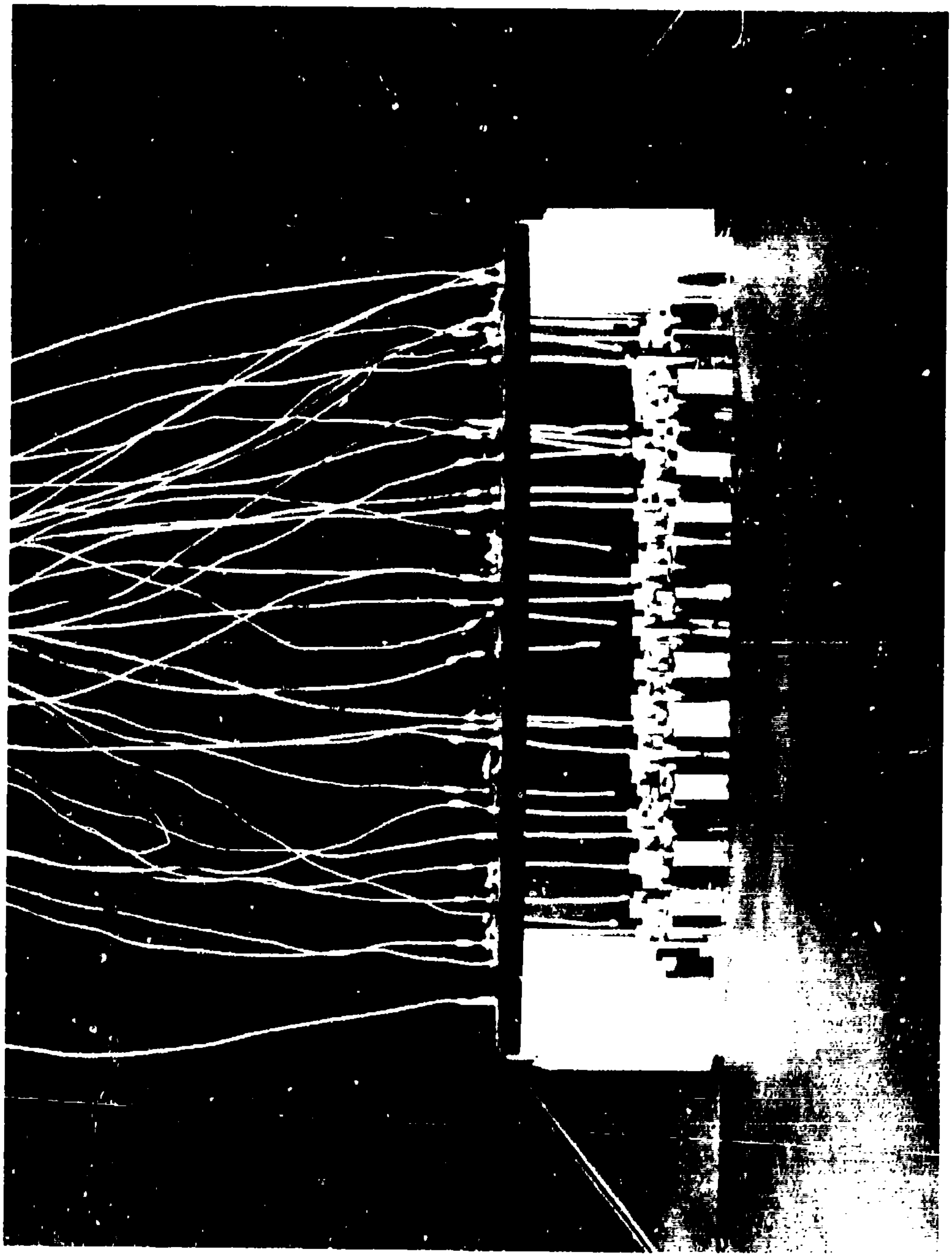

Figure 3.2 ABOVE-GROUND BERMED SHELTER MODEL WITH ONE WALL REMOVED SHOWING OCCUPANTS AND THERMOCOUPLES

ceiling plate was placed in position. Four of the five extra wires coming from the data logger were positioned to read the temperatures of air entering or leaving the model door and windows 1, 2 and 3. The fifth probe was used to read the free stream air temperature. A 1.2-KW electrical resistance heater with a fan and guide plates was positioned upstream of the model to provide warm air to fill the interior of the model.

3.2 Calibration Tests

Calibration runs for this series of tests were performed to establish a viable test procedure and to identify optimal values of air temperature differentials that would minimize errors due to the thermal capacity of model walls and provide repeatable results. The optimal heater locations and guide plate configurations that gave near uniform temperature rises for all the thermocouples were also determined. The following section describes the test procedure established from these calibration runs.

3.3 Test Procedure

Figure 3.3 shows the test setup for this series of tests. With the shelter model set at the proper angle on the turntable, the heater was placed upstream of it and switched on. The data logger was turned on to indicate the thermocouple readings. The rear wall openings (windows 3 & 4) were closed with thin metal strips for a few minutes to speed the temperature rise inside the shelter and to equalize temperature distribution. When the temperature was about 25°F to 28°F above ambient, the metal strips were removed and the wind tunnel blower was turned on and its speed regulated to provide the desired free stream wind speed. Air temperature inside the model was allowed to drop, falling by 6°F to 8°F in about 2 minutes. At this time, the heater was switched off and simultaneously pulled away to the top of the tunnel roof. The falling air temperatures inside the model were recorded by the data logger at twenty second intervals. (A sample recording is shown in Figure 3.4.)

The test was repeated at the second wind speed. The turntable was rotated for the next value of relative wind angle and the test repeated for the two different wind speeds. The thermocouple leads were then relocated at the

Figure 3.3 SETUP FOR TEMPERATURE-DECAY TESTS

[illegible] ABOVE-GROUND SHELTER TEMPERATURE DISTRIBUTION

TIME 100 200	01 LOC 1 LOC 17	02 LOC 2 LOC 18	03 LOC 3 LOC 19	04 LOC 4 LOC 20	05 LOC 5 LOC 21	06 LOC 6 LOC 22	07 LOC 7 LOC 23	08 LOC 8 LOC 24	09 LOC 9 LOC 25	10 LOC 10 LOC 26	11 LOC 11 LOC 27	12 LOC 12 LOC 28	13 LOC 13 LOC 29	14 LOC 14 LOC 30	15 LOC 15 LOC 31	16 LOC 16 LOC 32
15:32:00	84.2F 84.7F	85.3F 84.1F	85.4F 85.1F	84.7F 86.1F	85.9F 84.7F	84.3F 85.5F	84.5F 84.5F	84.3F 84.9F	86.1F 85.0F	84.9F 85.1F	84.9F 85.6F	85.9F 85.4F	85.4F 84.6F	86.0F 86.2F	84.7F 81.5F	86.5F 92.5F
15:37:00	83.5F 83.2F	84.4F 83.4F	85.1F 84.2F	83.8F 85.2F	85.0F 84.0F	83.8F 84.4F	83.6F 83.9F	83.4F 84.4F	85.3F 84.5F	84.0F 84.3F	84.2F 84.8F	85.5F 84.6F	84.7F 83.7F	85.2F 85.3F	83.8F 81.6F	85.5F 89.0F
15:39:20	83.7F 83.7F	84.2F 83.3F	84.9F 84.1F	83.6F 85.0F	84.7F 83.9F	83.6F 84.2F	83.4F 83.8F	83.3F 84.3F	85.0F 90.0F	83.9F 84.2F	84.0F 84.6F	85.2F 84.5F	84.5F 83.6F	85.0F 85.1F	83.7F 81.7F	85.2F 88.1F
15:40:04	83.7F 83.7F	84.2F 83.4F	84.9F 84.1F	83.6F 85.0F	84.7F 84.0F	83.7F 84.2F	83.4F 83.8F	83.4F 84.3F	85.0F 92.2F	84.0F 84.3F	84.1F 84.7F	85.3F 84.5F	84.6F 83.7F	85.0F 85.1F	83.7F 82.2F	85.2F 90.0F
15:42:00	119.9F 142.9F	153.9F 138.3F	138.8F 146.4F	152.7F 222.8F	167.0F 138.5F	132.1F 164.8F	150.9F 138.7F	138.7F 132.4F	193.4F 144.1F	145.5F 144.9F	147.0F 190.6F	121.3F 140.7F	130.6F 147.7F	156.4F 166.3F	146.6F 55.6F	184.0F 87.0F
15:42:40	100.0F 104.5F	107.3F 103.4F	105.0F 107.5F	108.7F 121.2F	111.6F 104.3F	101.9F 113.7F	108.1F 101.6F	106.8F 101.8F	115.4F 104.9F	107.6F 104.0F	106.0F 114.2F	101.4F 105.6F	103.5F 107.5F	111.3F 114.3F	107.4F 83.6F	114.2F 86.7F
15:43:00 t = 0	94.2F 98.6F	98.2F 95.8F	97.1F 98.6F	99.1F 105.9F	100.9F 96.6F	95.1F 102.3F	98.7F 94.7F	98.0F 95.3F	102.9F 98.0F	98.6F 97.7F	97.2F 104.1F	95.5F 97.6F	96.5F 97.9F	100.9F 102.7F	98.4F 81.1F	102.5F 87.4F
15:43:20	90.5F 92.5F	93.6F 92.6F	92.9F 94.6F	94.0F 98.5F	95.3F 93.0F	91.4F 96.9F	93.6F 91.9F	93.2F 92.1F	96.2F 93.4F	93.7F 93.1F	93.0F 96.3F	92.1F 93.0F	92.3F 93.2F	95.1F 96.5F	93.5F 80.7F	96.1F 99.1F
15:43:40	88.5F 90.4F	91.3F 90.1F	90.7F 91.7F	91.4F 94.4F	92.6F 90.4F	89.4F 93.2F	91.1F 89.9F	90.6F 89.9F	93.2F 90.9F	91.2F 90.8F	90.8F 93.0F	90.2F 90.6F	90.6F 90.8F	92.7F 93.5F	91.4F 80.5F	93.6F 89.4F
15:44:00	87.5F 89.0F	90.2F 88.8F	89.6F 90.4F	90.1F 92.6F	91.3F 89.1F	88.4F 91.5F	89.8F 88.8F	89.5F 88.8F	91.9F 89.7F	90.2F 89.7F	89.9F 91.5F	89.4F 89.6F	89.3F 89.5F	91.2F 91.8F	89.9F 80.5F	92.0F 89.8F
15:44:20	87.1F 88.4F	89.7F 88.2F	89.2F 89.7F	89.5F 91.7F	90.9F 88.5F	88.1F 90.6F	89.2F 88.4F	88.7F 88.3F	91.1F 89.1F	89.5F 89.2F	89.2F 90.8F	88.9F 89.1F	88.8F 88.9F	90.6F 91.0F	89.2F 80.7F	91.3F 90.2F
15:44:40	86.9F 88.1F	89.4F 87.7F	88.8F 89.2F	89.0F 91.1F	90.3F 88.2F	87.7F 90.0F	88.8F 88.1F	88.3F 88.1F	90.6F 88.7F	89.0F 88.9F	88.8F 90.4F	88.6F 88.7F	88.6F 88.5F	90.2F 90.5F	88.7F 80.8F	90.8F 90.4F
15:45:00	86.6F 87.8F	89.1F 87.5F	88.5F 89.0F	88.7F 90.8F	90.0F 87.9F	87.4F 89.7F	88.5F 87.9F	88.0F 87.9F	90.3F 88.5F	88.7F 88.6F	88.5F 90.0F	88.4F 88.4F	88.4F 88.4F	89.8F 90.2F	88.4F 80.9F	90.5F 90.7F
15:45:20	86.5F 87.6F	88.9F 87.3F	88.3F 88.8F	88.5F 90.5F	89.7F 87.8F	87.2F 89.5F	88.2F 87.7F	87.8F 87.7F	90.0F 88.3F	88.5F 88.4F	88.3F 89.8F	88.3F 88.2F	88.2F 88.1F	89.6F 89.9F	88.2F 81.0F	90.2F 90.9F

Figure 3.4 TEMPERATURE DISTRIBUTION (SAMPLE RECORDING)

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remaining 26 positions leaving the 27th thermocouple (location 45) as a reference point in its original location. The ceiling holes were sealed as before using tape. Tests were repeated for the same two angles and wind speeds as for the original 27 locations of the thermocouples. This completed the tests at the level of 1-5/8 inches above the floor. The thermocouple leads were then lowered so that they protruded 3-1/2 inches from the underside of the ceiling (1/2 inch from the floor). Similar tests were then repeated at this new height.

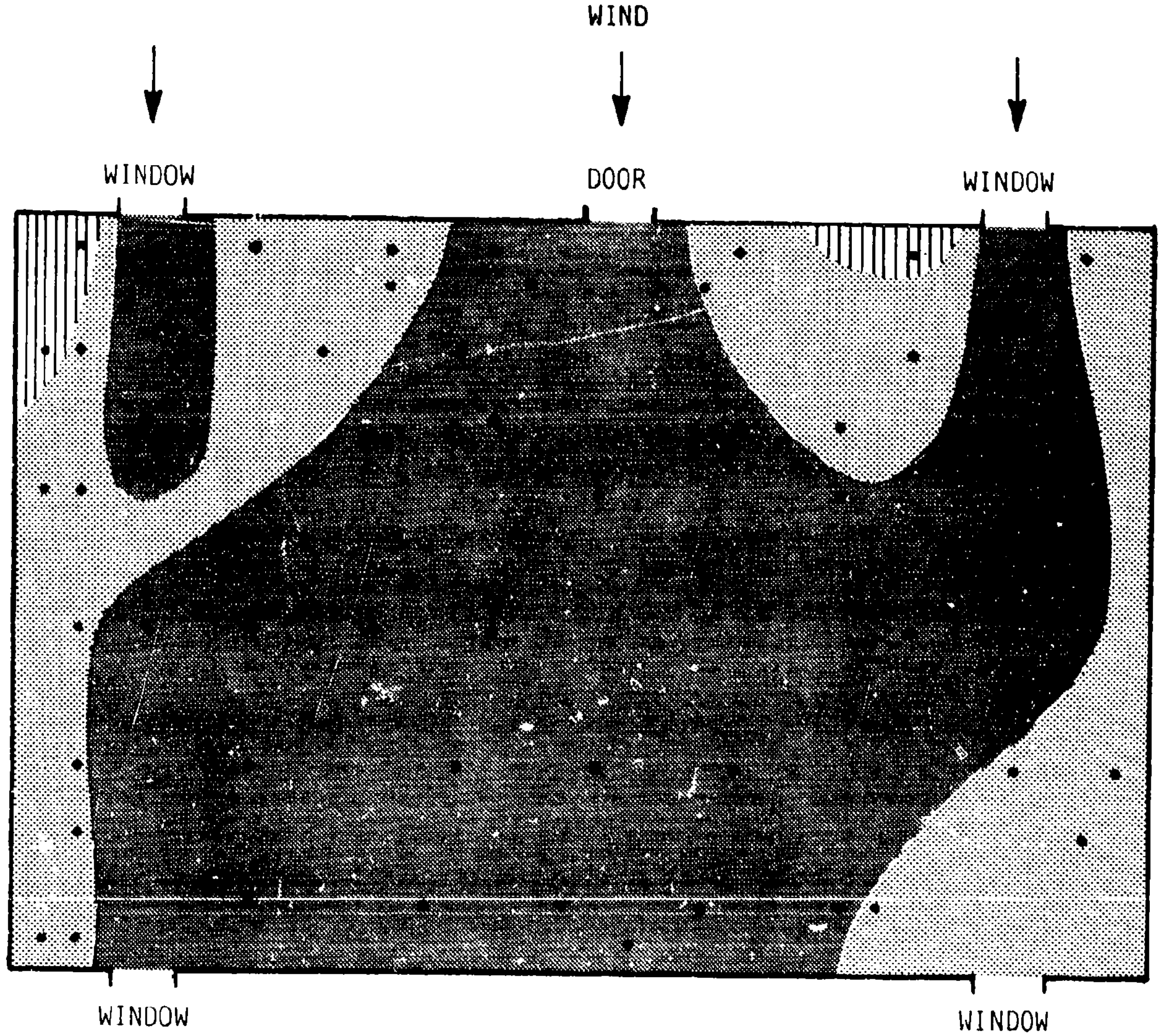
3.4 Data Reduction

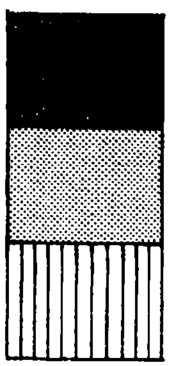
The temperature distribution inside the shelter at 20 seconds after switching off the heater was taken as the initial temperature distribution. The temperature of the common reference thermocouple location (location 45) at this time was approximately 19°F above that of the approaching free stream air temperature for all the test runs. Recordings of the data logger for the two different sets of thermocouple locations at this level (1-5/8 inches above the floor) were combined to give temperature-time histories of 53 locations inside the shelter model for each wind angle and wind speed. From these data, three minute temperature drops for the 53 locations were tabulated. (At the higher wind speeds, nearly 80% of the total drop and at the lower wind speeds, 65% of the total drop occurred in 3 minutes.) At a wind speed of 12.7 fps and relative wind angle of 45°, the largest temperature drop recorded was 15.9°F. Temperature drops among all the remaining 52 locations varied from 6.2°F to 14.6°F. The span of 8.4°F covering the temperature drops of all locations except that of the largest drop* was divided into 3 zones. Zone I covered locations of temperature drops varying from 6.2°F to 9.0°F, Zone II covered those with temperature drops from 9.0°F to 11.8°F and Zone III spanned locations with temperature drops of 11.8°F and higher. These zones were labelled as zones of poor, moderate and good ventilation (fresh air mixing), respectively.

3.5 Results and Discussions

Results of the analysis of air mixing at elevations of 1/2 inch and 1-5/8 inches from the floor (corresponding to full-scale values of 18 inches and 60 inches, respectively) are shown in Figures 3.5 - 3.12. These figures clearly

* This location was directly in the path of the fresh air stream and had temperature drop considerably higher than those of the rest.





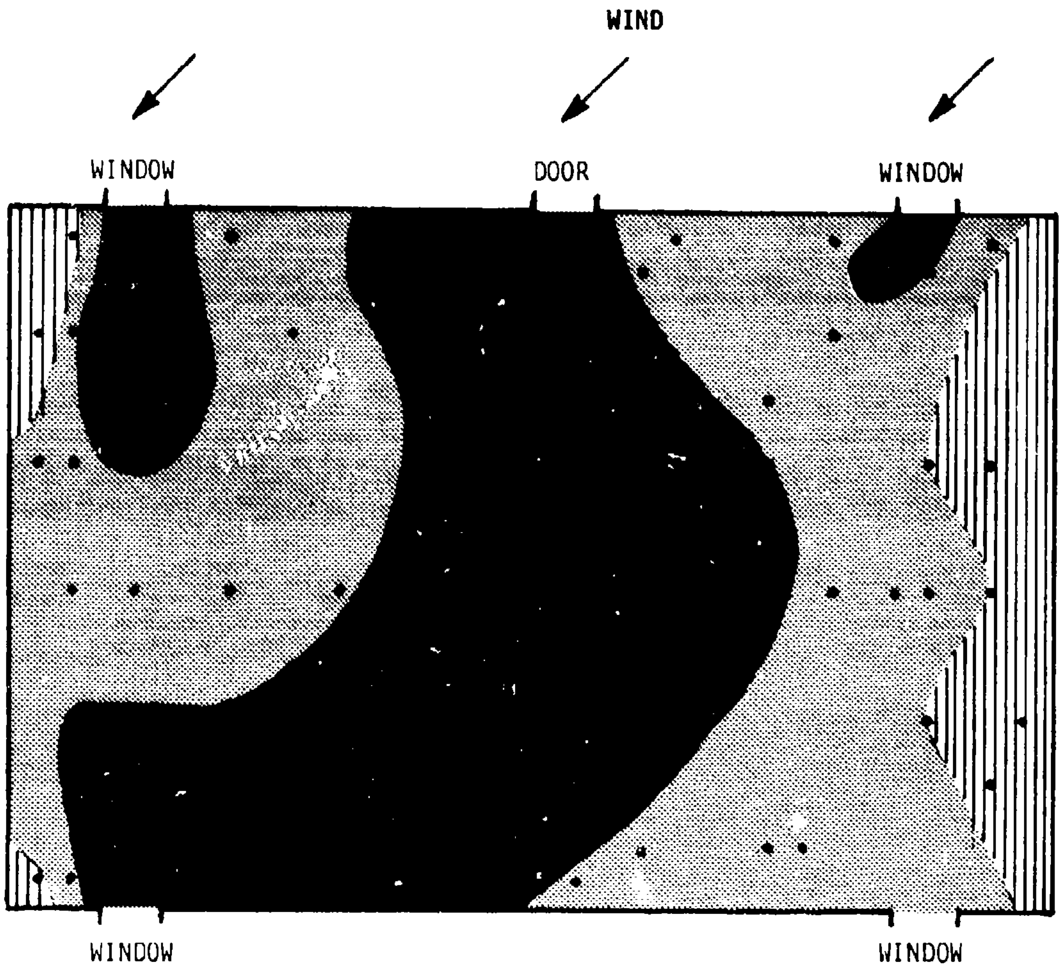
Areas of good ventilation, Temperature drop 11.8°F to 14.6°F.

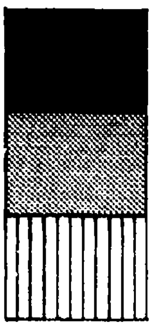
Areas of moderate ventilation, Temperature drop 9°F to 11.8°F.

Areas of poor ventilation, Temperature drop less than 9°F.

Wind speed = 12.7 fps
Relative wind angle = 0 deg.
Height above floor = 1-5/8 in.

Figure 3.5 AIR FLOW DISTRIBUTION





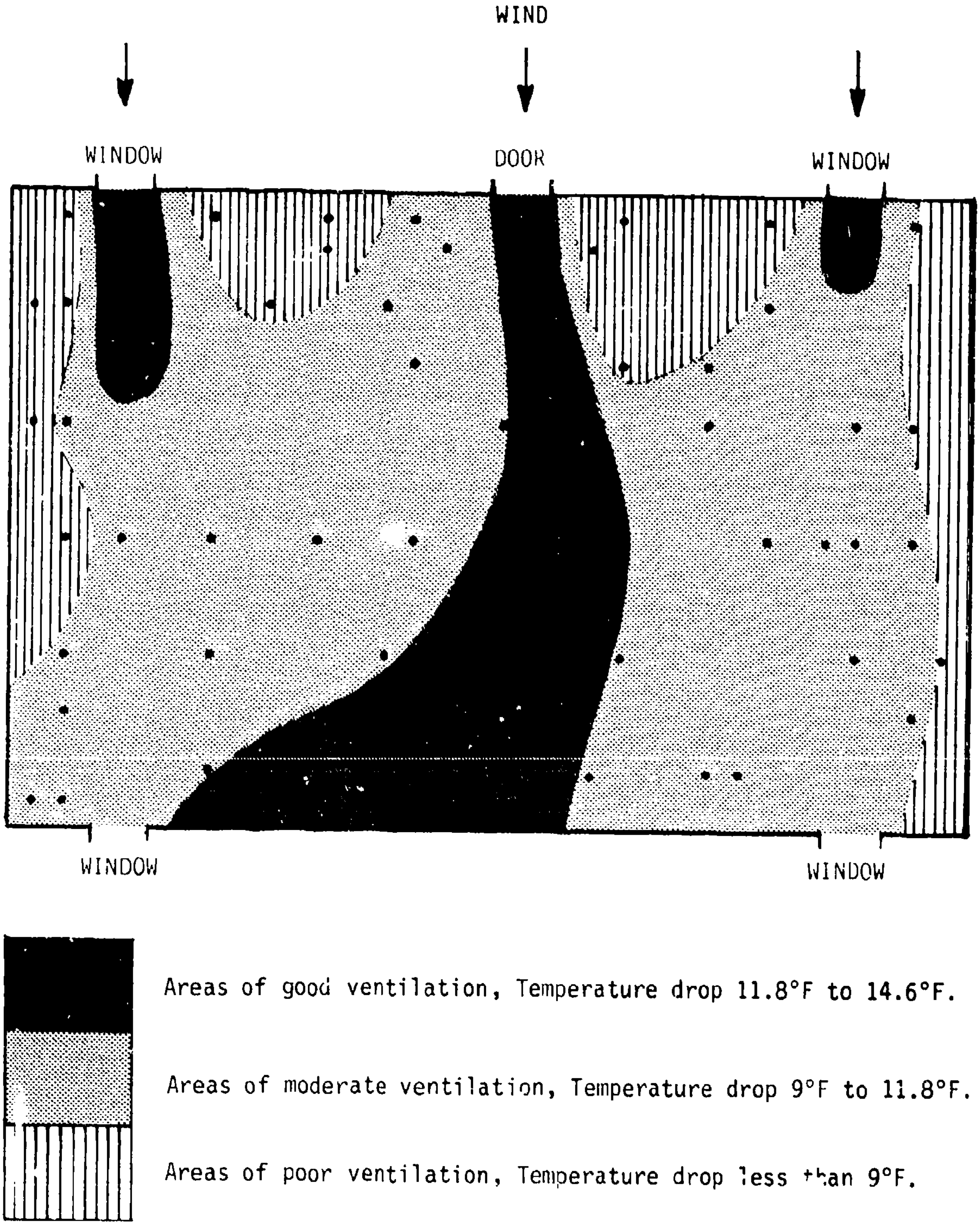
Areas of good ventilation, Temperature drop 11.8°F to 14.6°F.

Areas of moderate ventilation, Temperature drop 9°F to 11.8°F.

Areas of poor ventilation, Temperature drop less than 9°F.

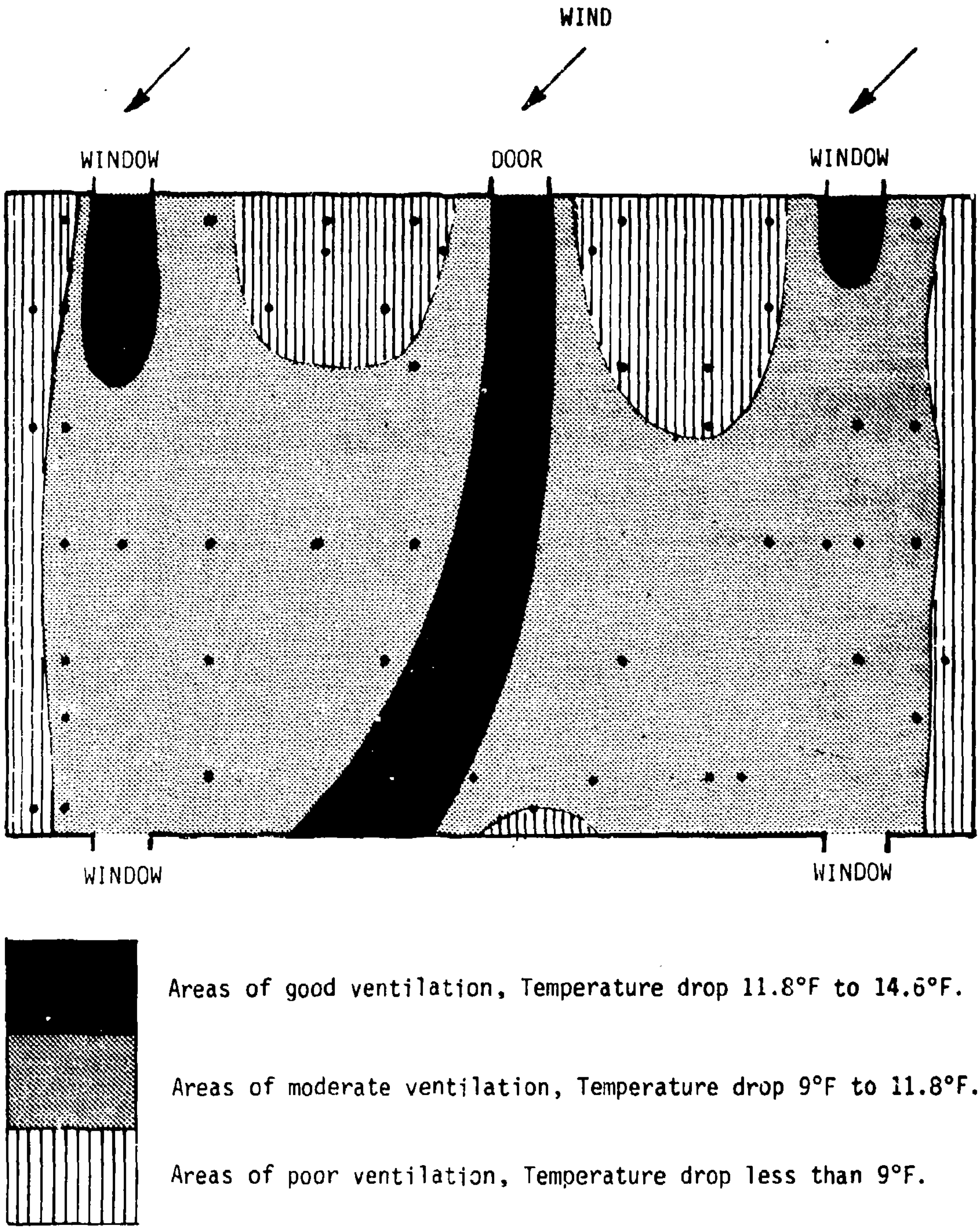
Wind speed	=	12.7 fps
Relative wind angle	=	45 deg.
Height above floor	=	1-5/8 in.

Figure 3.6 AIR FLOW DISTRIBUTION



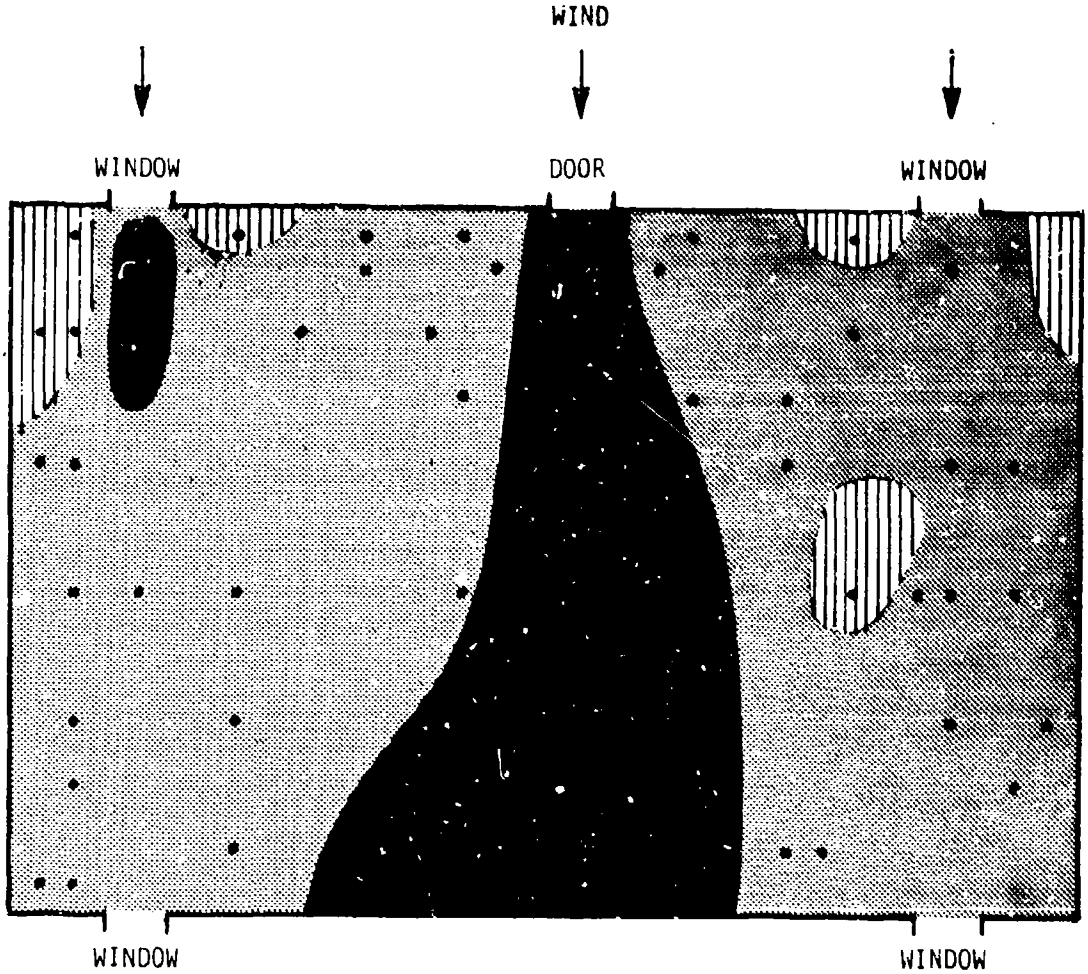
Wind speed = 5.5 fps
Relative wind angle = 0 deg.
Height above floor = 1-5/8 in.

Figure 3.7 AIR FLOW DISTRIBUTION



Wind speed = 5.5 fps
Relative wind angle = 45 deg.
Height above floor = 1-5/8 in.

Figure 3.8 AIR FLOW DISTRIBUTION



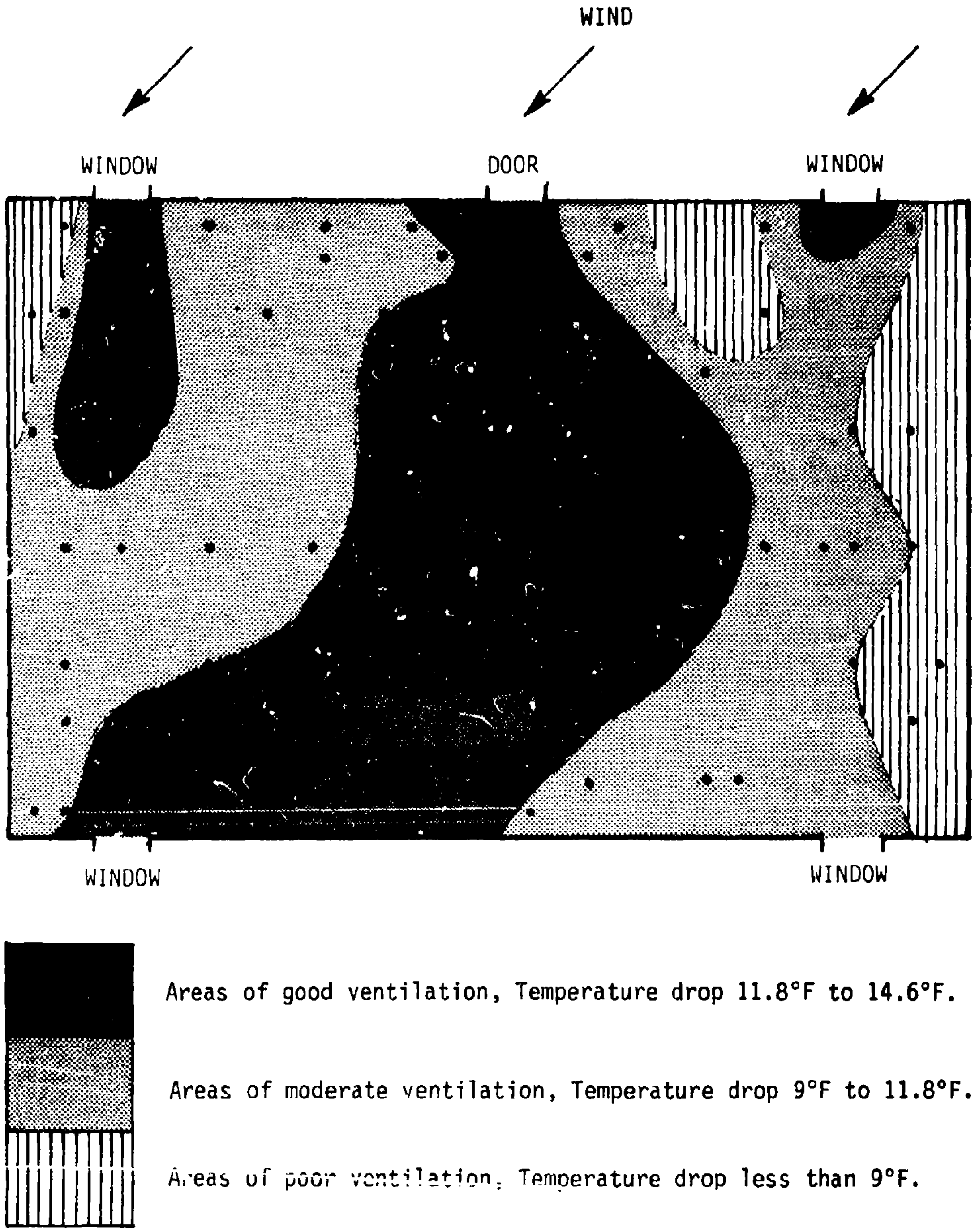
Areas of good ventilation, Temperature drop 11.8°F to 14.6°F.

Areas of moderate ventilation, Temperature drop 9°F to 11.8°F.

Areas of poor ventilation, Temperature drop less than 9°F.

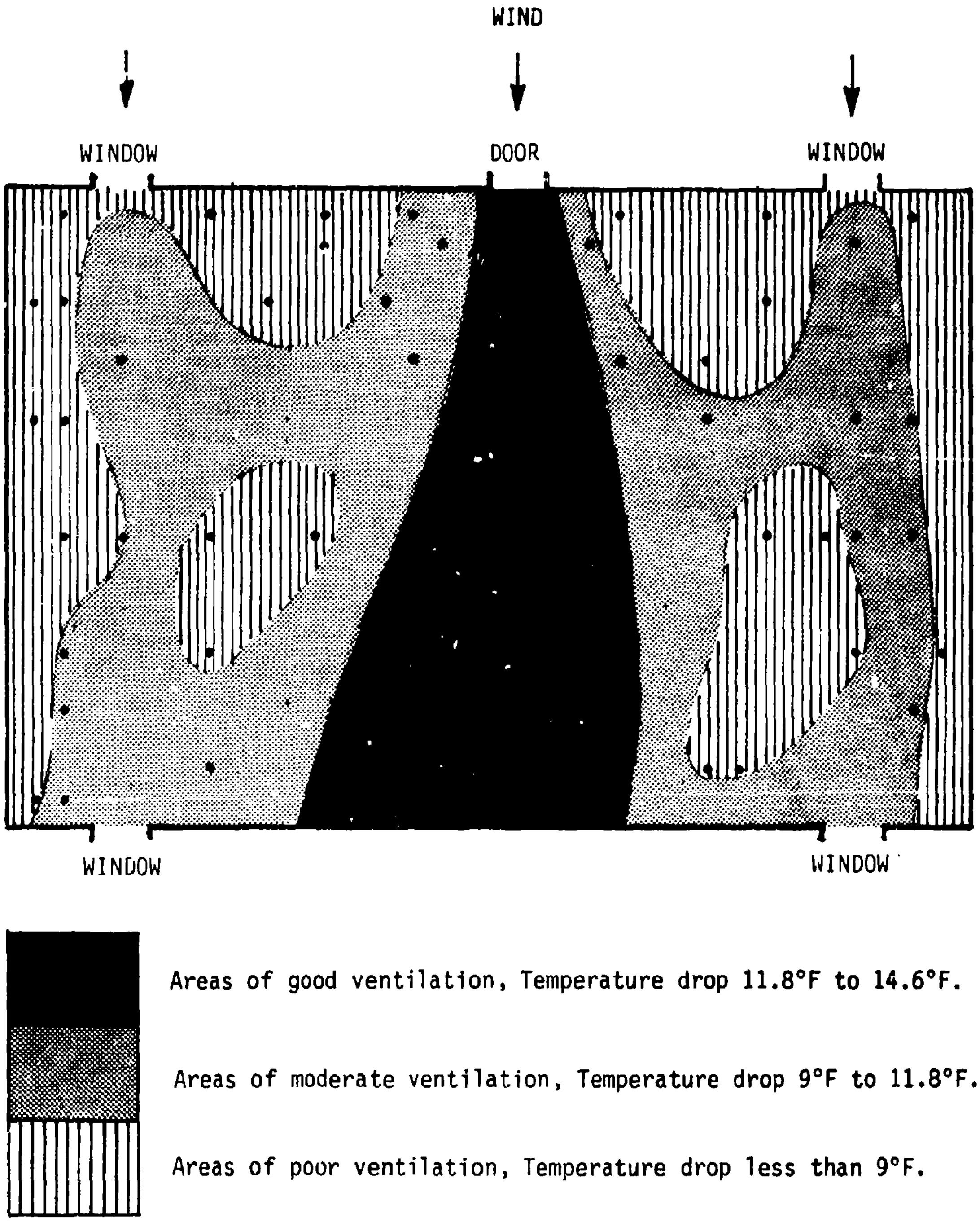
Wind speed = 12.7 fps
Relative wind angle = 0 deg.
Height above floor = 0.5 in.

Figure 3.9 AIR FLOW DISTRIBUTION



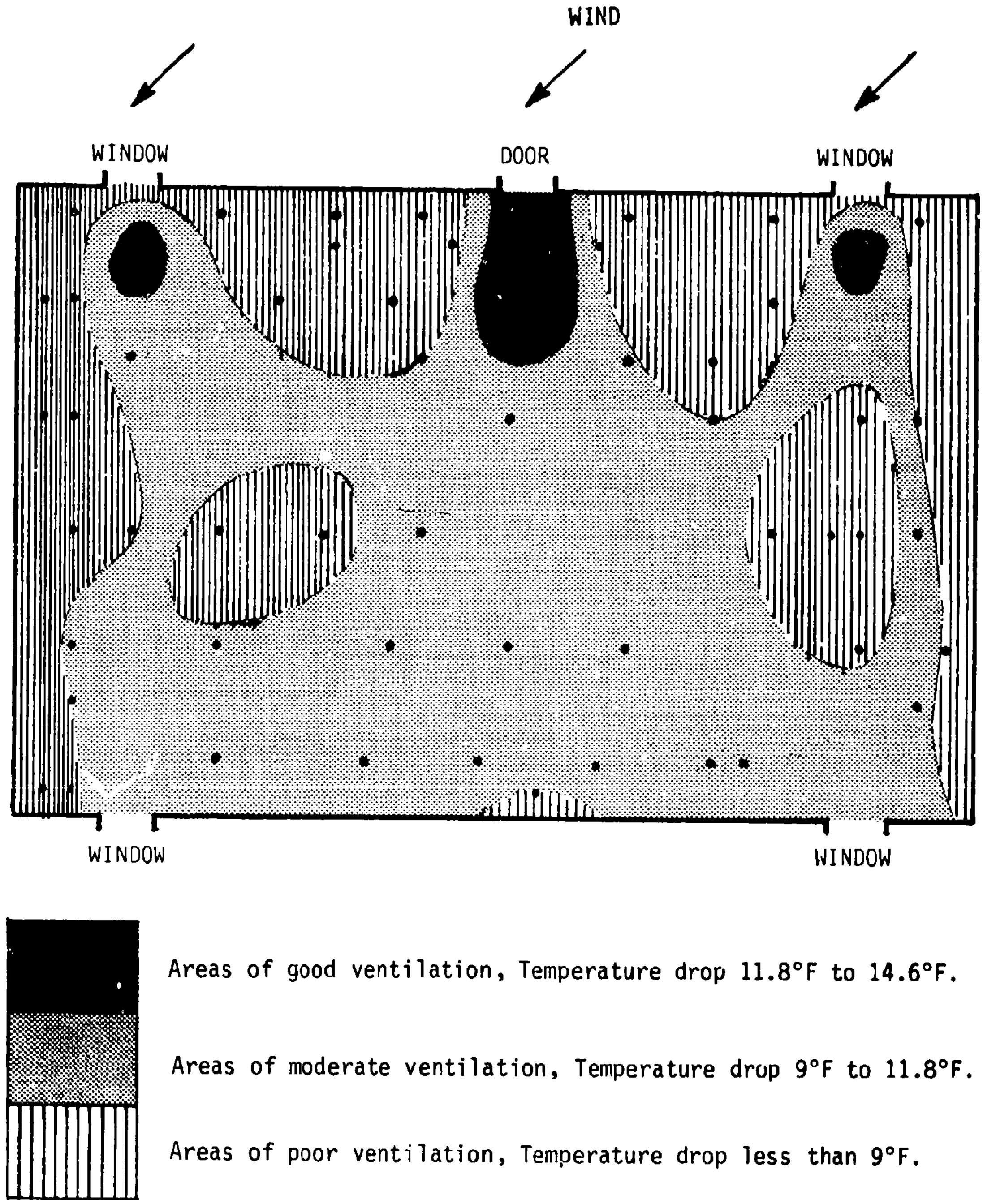
Wind speed = 12.7 fps
Relative wind angle = 45 deg.
Height above floor = 0.5 in.

Figure 3.10 AIR FLOW DISTRIBUTION



Wind speed = 5.5 fps
Relative wind angle = 0 deg.
Height above floor = 0.5 in.

Figure 3.11 AIR FLOW DISTRIBUTION



Wind speed = 5.5 fps
Relative wind angle = 45 deg.
Height above floor = 0.5 in.

Figure 3.12 AIR FLOW DISTRIBUTION

underscore the dependence of air mixing on both wind speed and relative wind angle. The following observations can be made from the results:

- Although ventilation throughputs (Q) are nearly the same, the proportion of poorly ventilated shelter area at the upper level is larger for θ equal to 45° than for θ equal to 0°. This is true for both values of wind speed tested (Figure 3.5 versus 3.7 and 3.9 versus 3.11).
- At the lower wind speed, significantly greater proportions of shelter area are poorly ventilated than at the higher wind speed at both elevations and relative wind angles (Figures 3.7, 3.8, 3.11, and 3.12 versus 3.5, 3.6, 3.9, and 3.10).
- In general, the proportion of poorly ventilated area is considerably larger at the lower elevation than at the higher elevation (Figures 3.5, 3.7, and 3.8 versus 3.9, 3.11, and 3.12). However at the higher wind speed, for θ equal to 45°, air mixing at the upper elevation is only marginally better than at the lower elevation.

One very important piece of information to be drawn from this qualitative analysis of air distribution relates to the adequacy of natural ventilation in upgraded shelters. Ventilation requirements for shelter occupants are known to range from 3 cfm to 50 cfm per person, depending on the geographical location. Taking an intermediate value of 20 cfm per person, the required ventilation throughput for the full-scale shelter occupied at the rate of 10 square feet per person is approximately 3000 cfm (for 150 occupants). Assuming 25% to 30% of this is generated by thermal forces (thermally induced ventilation in a somewhat similar shelter was measured to be about 950 cfm, Ref. 1), the minimum wind speed necessary to provide the remaining 2100 cfm of air flow can be read as approximately 8.5 mph (12.7 fps) from Figure 2.12. However, this calculation assumes uniform air distribution inside the shelter which, as explained earlier, may not exist in many cases. It would therefore be necessary to provide for a higher rate of ventilation throughput than the minimum calculated and/or create better air mixing inside the shelter. These may be achieved by incorporating devices such as Kearny pumps, PVK units or innovatively designed flow enhancement devices and properly located expedient wall openings.

Section 4

BELOW-GROUND SHELTER

This task of the overall study is aimed at evaluating the feasibility of adequately ventilating single-chamber below-ground shelters of the key worker type using wind-induced air flow. The scope of the study under the present phase is limited to concepting innovative designs of expedient FEDs, establishing a test scheme, designing and fabricating the model and carrying out preliminary runs to assess qualitatively the extent of flow enhancement obtainable with these devices.

4.1 Shelter Geometry

A single-chamber shelter (36 feet x 36 feet x 8 feet) capable of accommodating approximately 100 key workers was selected for this study. Stairways at 45° to the ground surface lead to centrally located doors (3 feet wide x 6 feet high) on each side wall. The shelter roof is approximately 3 feet below the surface of the ground. Figure 4.1 shows a schematic of the shelter with one concept of an FED placed around each stairway opening.

4.2 Fabrication of Model

The model was fabricated out of 3/16-inch thick clear Plexiglas sheets. Bottom sides of the ceiling of the shelter and the stairways were painted black for photographic recording of the tracer bubbles. One side wall together with its stairway was removable to facilitate placement of simulated occupants. All the remaining joints were cemented. The model was suspended from a clear Plexiglas turntable by four long bolts with counter-sunk heads at the top. Figures 4.2 and 4.3 show photographs of the model, one looking from above through the turntable and the other as viewed from below.

4.3 Calibration Tests

Preliminary test runs were made with a simple design of an FED as shown in Figure 4.4. This design has three vertical sides and a roof plate. Dimension A, B and H were taken as 2 inches each (corresponding to 6 feet for the full-scale shelter). One FED was placed around each stairway opening

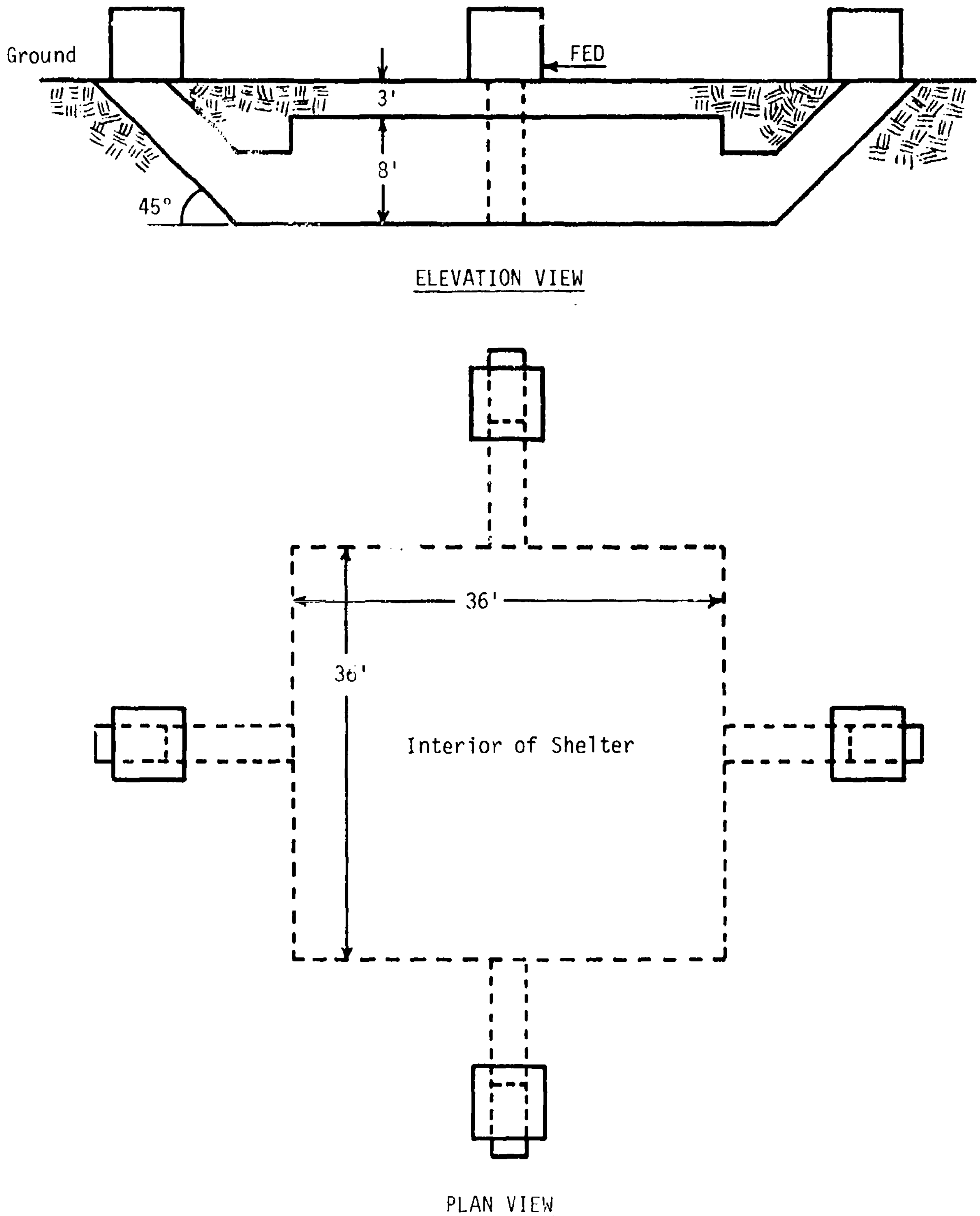


Figure 4.1 BELOW-GROUND SHELTER WITH 'FED'

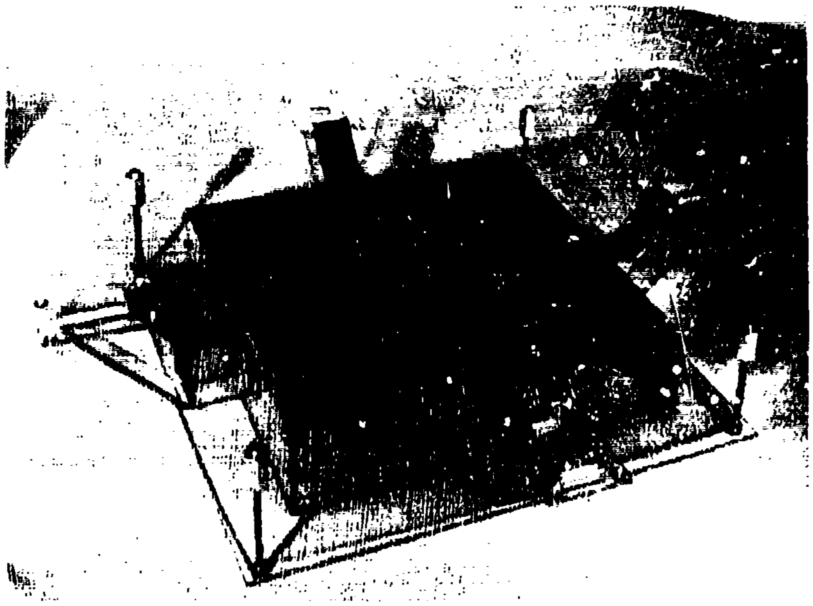


Figure 4.2 BELOW-GROUND SHELTER - VIEWED FROM ABOVE THE MODEL

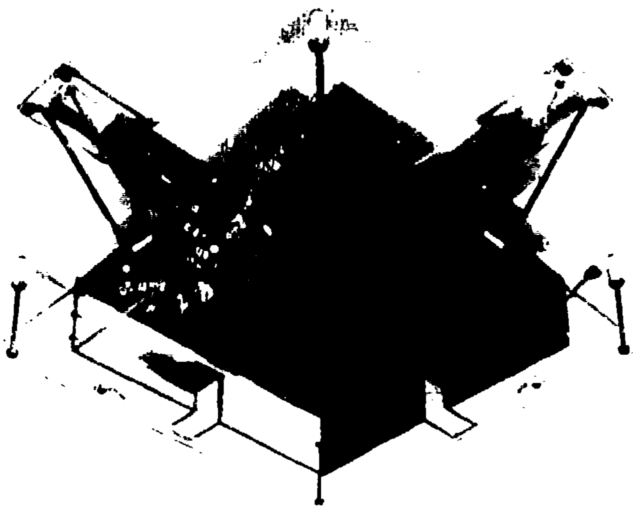


Figure 4.3 BELOW-GROUND SHELTER - VIEWED FROM BELOW THE MODEL

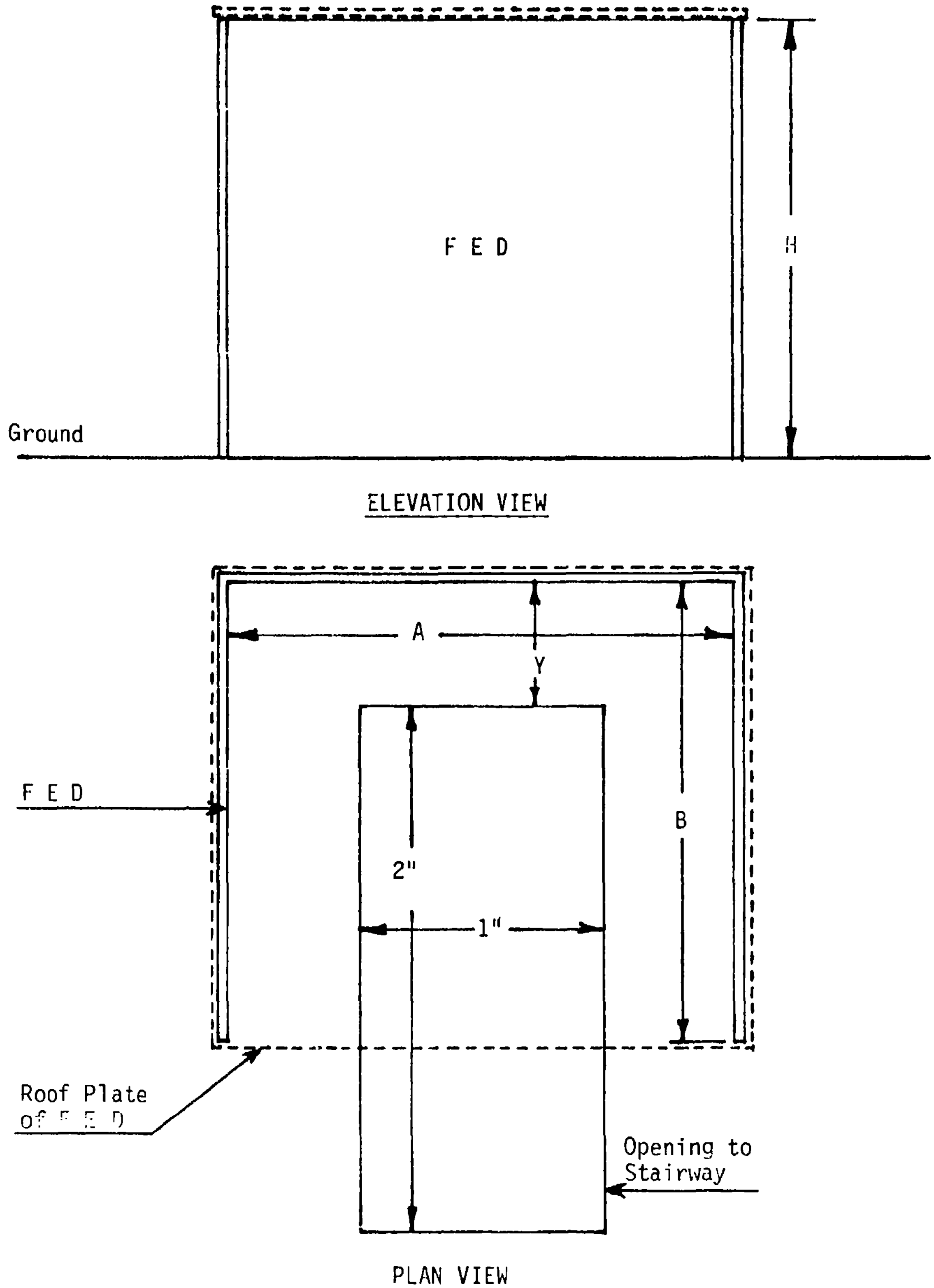


Figure 4.4 TYPICAL 'FED' LAYOUT AROUND A STAIRWAY OPENING

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such that they created positive pressure zones above the openings on the windward sides and negative pressure zones on the leeward sides. Trial runs were made for wind speeds in the range of 5 fps to 15 fps and relative wind angles of 0° and 15°. Tracer bubble flow through the model was visually observed to obtain a reasonably good starting value of the variable (y) and to estimate the effects of design modifications such as eliminating roof plates from the FEDs or using only two FEDs in place of four. The following general observations were made from these runs:

- Shelter ventilation throughput appeared to be considerably enhanced by the FEDs when the distance (y) was not more than about one half inch (full-scale value, 3 feet).
- The contribution of the roof plates of the FEDs to ventilation throughput seemed to be significant.
- Reductions in ventilation throughput when FEDs were used around the front and rear stairway openings only (with those on the sides removed) seemed to be significant.

4.4 Recommendations for Below-ground Model Tests

It appears that ventilation rates of significant magnitude from wind forces alone can be obtained by the use of simple and inexpensive designs of FEDs (such as an arrangement of sandbags) for single-chamber below-ground shelters. Further tests are therefore warranted. These must be directed toward determining optimum values of design variables such as A, B and H, as well as investigating simple modification, for practical values of the dimensions of the stairway openings. Correlations of the ventilation throughput with wind speed over the range of relative wind angles of interest must also be made along with an analysis of interior air distribution.

Section 5

SUMMARY AND RECOMMENDATIONS

Wind-induced ventilation air flow for the fallout shelter studies was found to be primarily a function of wind speed. For shelter orientations at which the wall with the larger opening area is on the windward side, the ventilation throughput is slightly higher (6% to 18%) than for orientations at which it is on the leeward side. Even for nearly head-on winds hitting the wall without openings, the ventilation throughput is not much less than its value at any other angle.

The study establishes air distribution as an important factor to be considered in the analysis of occupant comfort level. Air distribution inside the shelter at any given elevation depends strongly on the wind speed and to a lesser extent on the relative wind angle. For values of meteorological wind speed greater than about 8 mph, the shelter air distribution at both elevations tested (full-scale elevations of 60 inches and 18 inches above floor level) seemed to be reasonably good.

One infers from the extrapolated full-scale results of Figure 2.12 and the data presented in Chapter 11 of Reference 16,* that a shelter similar to the one studied would meet the ventilation requirements for an effective temperature of 83°F and 90% adequacy over a significant portion of the United States, given moderate wind speed conditions. Typical values of ventilation rates projected for the full-scale shelter, when occupied at the rate of 1 person per 10 square feet, vary from 13 cfm per person at a wind speed of 8 mph to 25 cfm per person at a wind speed of 13 mph (meteorological). It is also observed that the ventilation throughput ($\simeq$ 900 cfm) generated by a 3 mph (4.5 fps) wind equals that generated by body heat from 150 simulated occupants (occupant density of 1 person per 10 square feet) in the somewhat similar full-scale shelter studied in Reference 1.

---

* Reference 16 indicates that a ventilation rate of 7.5 to 40 cfm per person is adequate to maintain an effective temperature of 83°F with an adequacy of 90%.

Ventilation throughput and air distribution are complex functions of several independent variables. To analyze or evaluate air volume flow rate or air distribution in shelters with significantly differing geometries or areas and locations of wall openings, separate model studies will be necessary. Simple extrapolations/interpolations of available results could lead to grossly incorrect conclusions. Model tests may also be required to evaluate the effects of expedient wall openings or modifications of internal partitions on ventilation throughput and air distribution. Random additions of expedient wall openings may shortcircuit the air flow, resulting in an increase of ventilation throughput, but causing poor air distribution. In shelters with sufficiently large values of ventilation throughput, and poor air distribution, the permissible occupant density may also be significantly improved by adding mechanical units such as Kearny pumps and pedal ventilators.

The preliminary tests on wind-induced ventilation of a single-chamber below-ground shelter made with a simple design of a flow enhancement device (FED) show promising results. Air volume flow rate through the model appears to be considerably enhanced by properly located FEDs even at moderate wind speeds. Additional studies to optimize the design and location of FEDs and to qualitatively evaluate their effectiveness are strongly recommended.

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APPENDIX

DESCRIPTION OF WIND TUNNEL

APPENDIX

DESCRIPTION OF WIND TUNNEL

The wind tunnel used in this study (Figures A.1 and A.2) is situated in a large room that forms the return circuit between the inlet and the exhaust. Free stream velocities of up to 25 fps can be generated in its test section (60 in. wide x 30 in. high) with the present blower and variable speed drive. The test section is fabricated of clear Plexiglas sheets and has an access door located on the side wall. A "momentum defect generator," consisting of a counter-jet manifold and a set of transversely laid slats, located a short distance downstream of the intake section, provide thick boundary layers of the type required for the present study.

Precision hot-wire anemomete and Pitot-static tubes in conjunction with precision manometers provide velocity and pressure profiles in the tunnel's test section and also at a section 30 in. upstream of it. A tracer bubble system that consists of high-pressure helium and air tanks, a three-channel bubble generator console, vortex filters, and bubble release tubes delivers neutrally bouyant bubbles of high stability for flow tracing.

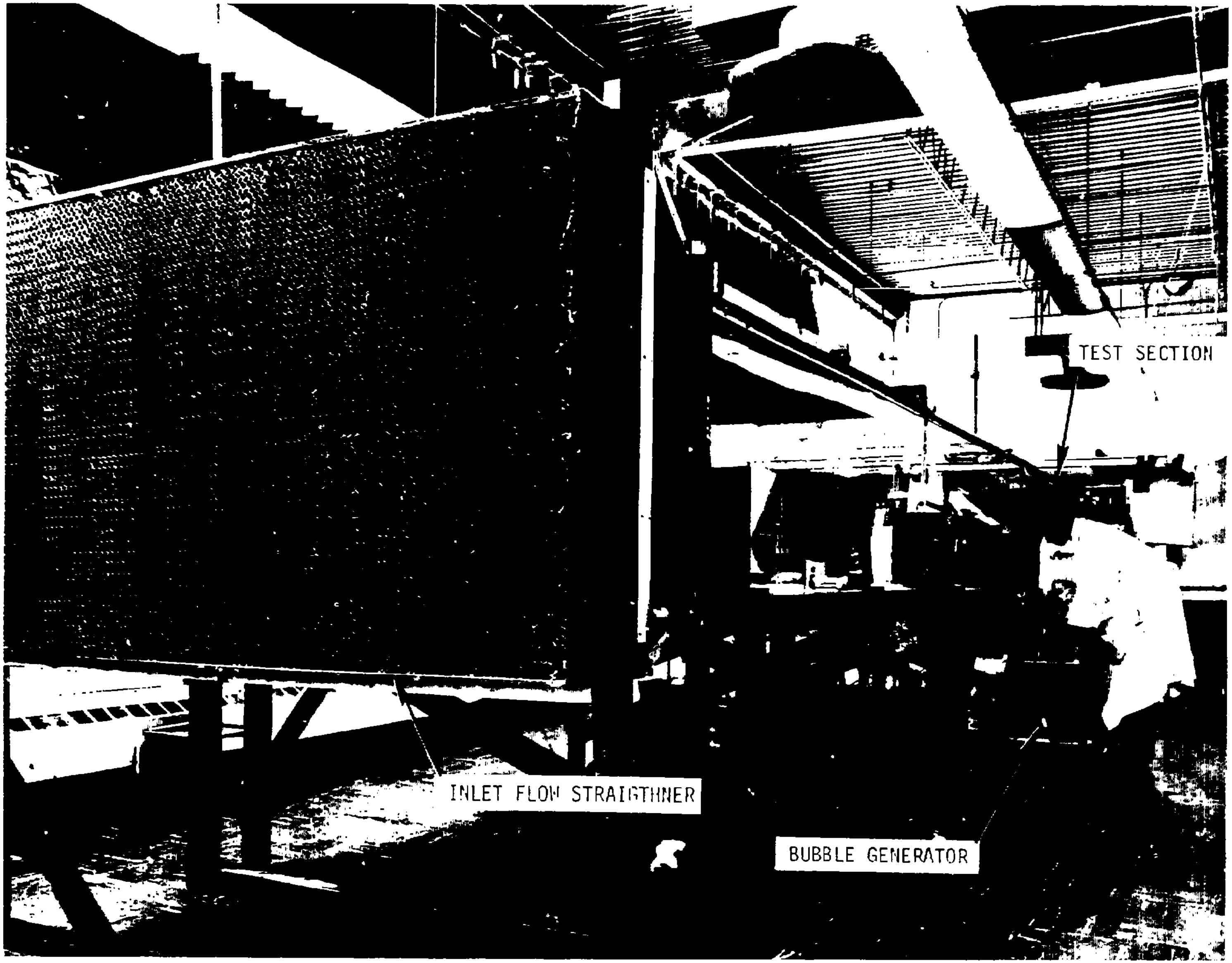

Figure A.1 LOW SPEED WIND TUNNEL LOCATED IN GARD LABORATORY BUILDING, NILES, ILLINOIS

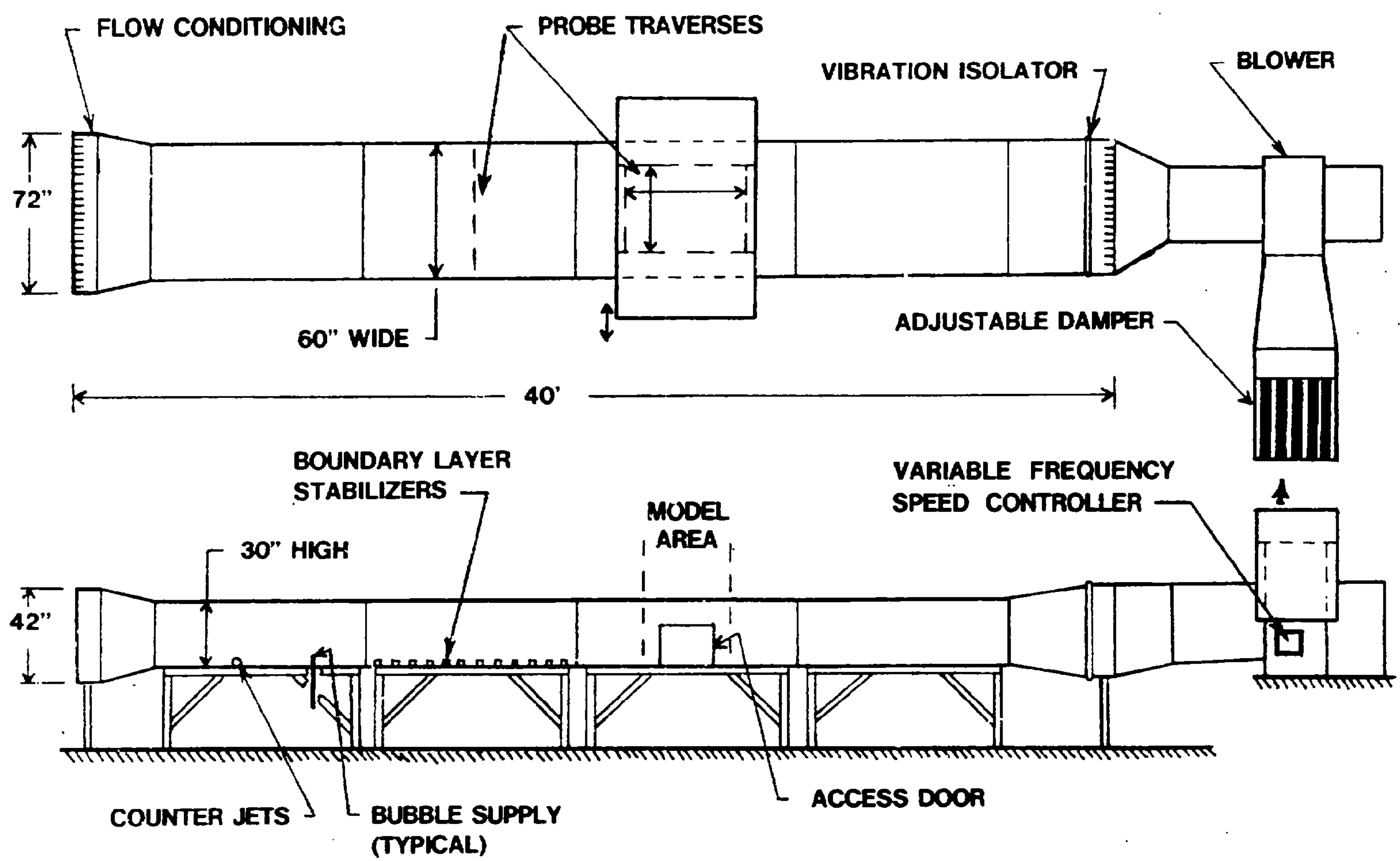

Figure A.2 SCHEMATIC OF WIND TUNNEL

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Evaluation of Shelter Ventilation by Model Tests
GARD Final Report AI-51
FEMA Contract No. EMW-C-0633, FEMA Work Unit 1217I
by C. K. Krishnakumar, J. B. Koh, S. F. Fields, R. H. Henninger
March 1983 (UNCLASSIFIED) pp 72

Scale model tests using a low speed wind tunnel were performed to determine the wind-induced ventilation throughput in an earth-bermed, single-room, above-ground shelter over a wide range of approach wind velocities. Air flow through the wall openings and the interior of the model was traced with neutrally bouyant tracer bubbles and recorded using a movie camera. Volume flow rate through a door or window opening was determined by taking the product of the average bubble velocity, the area of the opening and an experimentally determined area coefficient. Model ventilation throughput values were obtained by adding the air volume flow rates through all the inlet openings and the full-scale values were projected using scaling laws. Air distribution (fresh air mixing) inside the shelter was also analyzed for different approach wind conditions using a temperature-decay method.

A simple design of a Flow Enhancement Device (FED) which could significantly improve wind-induced ventilation in a below-ground shelter was concepted. A scale model of a 100-person, key worker type below-ground shelter was fabricated and preliminary runs were made with it.

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GARD Final Report AI-51
FEMA Contract No. EMW-C-0633, FEMA Work Unit 1217I
by C. K. Krishnakumar, J. B. Koh, S. F. Fields, R. H. Henninger
March 1983 (UNCLASSIFIED) pp 72

Scale model tests using a low speed wind tunnel were performed to determine the wind-induced ventilation throughput in an earth-bermed, single-room, above-ground shelter over a wide range of approach wind velocities. Air flow through the wall openings and the interior of the model was traced with neutrally bouyant tracer bubbles and recorded using a movie camera. Volume flow rate through a door or window opening was determined by taking the product of the average bubble velocity, the area of the opening and an experimentally determined area coefficient. Model ventilation throughput values were obtained by adding the air volume flow rates through all the inlet openings and the full-scale values were projected using scaling laws. Air distribution (fresh air mixing) inside the shelter was also analyzed for different approach wind conditions using a temperature-decay method.

A simple design of a Flow Enhancement Device (FED) which could significantly improve wind-induced ventilation in a below-ground shelter was concepted. A scale model of a 100-person, key worker type below-ground shelter was fabricated and preliminary runs were made with it.

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